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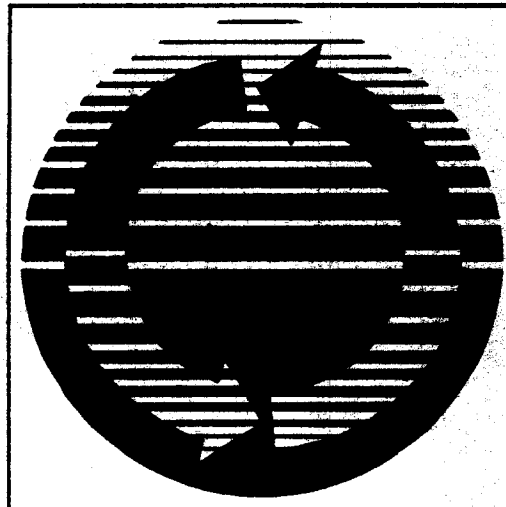
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**PROGRESS REPORT
REGENERATIVE LIFE SUPPORT SYSTEM
RESEARCH
DURING THE PERIOD
SEPTEMBER 1987 - MARCH 1988
NASA Grant No. NAG 9-253**

Prepared by

**The Regenerative Concepts Team
Texas A&M University**



Submitted to:

**NASA Johnson Space Center
Houston, Texas 77058
Through
Texas A & M Research Foundation**

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**Conceptual Design for a Food Production,
Water and Waste Regeneration Module
NASA Grant No. NAG 9-253**

**Team Leader: Oran W. Nicks
Director, Space Research Center
Texas Engineering Experiment Station**

**Technical Monitor: Dr. Hatice S. Cullingford
Solar System Exploration Division
NASA Johnson Space Center**

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CONTENTS

SECTION I. SUMMARY 1

SECTION II. MODELING

Chapter 1. RECON Systems Design and Modeling Tools Achievements	5
Chapter 2. A Time-Step Simulation Model for a Life Support System	49
Chapter 3. A Preliminary Comparison of CELSS Concepts	73

SECTION III. INTERDISCIPLINARY RESEARCH

Chapter 1. Interdisciplinary Research Laboratory	103
Chapter 2. The Design of Waste Treatment Technology Suitable for a Space-Flight Food Regeneration Module	109
Chapter 3. Advances in Algae Growth Experimental Apparatus	125
Chapter 4. Algal Models	131
Chapter 5. Plant Growth Under Low Atmospheric Pressure	139
Chapter 6. Higher Plant Growth Model	151
Chapter 7. Control of CO ₂ Concentration through Temperature Effects on Plant Growth	179
Chapter 8. Artificial Chloroplast	197
Chapter 9. Investigations of Lunar Soil Simulants	227
Chapter 10. Food Processing in Life Support Systems	229
Chapter 11. Preliminary Studies for an Enclosed Crop Growth Chamber on the Moon	233

Appendices

Appendix A. Controlled Environmental Life Support Systems Research Conference	243
Appendix B. Details of Steady State Model	265
Appendix C. Bosch and Sabatier Subsystem Comparison for the CO ₂ Reduction Process	301

SECTION I

SUMMARY

Prepared by

O.W. Nicks
Space Research Center

Section I

SUMMARY

Introduction

The Regenerative Concepts (RECON) Team is an interdisciplinary group of scientists and engineers at Texas A&M University who have been involved in life support systems research and related fields since May 1986. In addition to joint modeling and design study efforts which occupy the group as a whole, activities include individual research by members in their special fields. This report covers activities and progress during the period from September 1, 1987 through March 31, 1988.

Since the beginning of the current research grant, the RECON Group has held regular meetings, with an average attendance of over fifteen people per meeting, to plan and coordinate modeling and interdisciplinary research activities, to report progress on the current grant, and to discuss topics for future study. The RECON Team members funded on the grant included:

O.W. Nicks, F.E. Little, G.C. Johnson	Space Research Center
C.O. Patterson	Biology
R. Kainthla, D. Hitchens	Chemistry
A. Garcia	Agricultural Engineering
D. Spence	Industrial Engineering
M. Holtzapple	Chemical Engineering
R. Drees	Soil & Crop Sciences
W.M. Moses	Mechanical Engineering
M. Makela	Knowledge Engineering Lab (Entomology)

Because of their interest in life support systems, several other researchers have been participating in the group activities, although they are not directly funded by the current grant. Many of these are making significant contributions by bringing related skills and background information to address life support technologies. Some are conducting research on chemical systems, thermal control technologies, on food protein processes, on biological phenomena, on plant growth, on agricultural production, on artificial intelligence and knowledge engineering technologies.

Other contributors are:

B. Murray	Adjunct Research Engineer, TEES
J. Holste	Chemical Engineering
F. Van Duker	Chemical Engineering
G. Peterson	Mechanical Engineering
T. Rogers	RECON Lab, Mechanical Engineering
J. Bockris	Chemistry
E. Rykiel	Industrial Engineering
P. Sharpe	Industrial Engineering
H. Slater	Industrial Engineering
B. Wright	Agricultural Engineering
T. Hall	Biology
H. Preisig	Chemical Engineering
J. Wagner	Food Protein Research Center
D. Whittaker	Agricultural Engineering
H. Wu	Industrial Engineering
K. Marsh, B. Gammon	Thermodynamics Research Center
L. Wilding	Soil and Crop Sciences
R. Mayer	Knowledge Based Systems Laboratory (TEES)

Smaller *ad hoc* research teams have been formed for specific topics. These teams have functioned independently from the RECON group as a whole, reporting progress to and seeking feedback from the group during the weekly meetings. In this way, the small teams have been very productive, especially on modeling and design efforts, while still maintaining the group interactions with the entire team.

Several invited guests participated in RECON meetings and contributed to the general knowledge of the group, several technical conferences were attended, and visits were made with other researchers who are involved in life support systems research. RECON meeting visitors included Ferolyn Powell, Life Systems, Inc., and William Bowie, Krug International, Inc., Kamel Fotouh, Paul Biney, and Ronald Boyd from Prairie View A&M University, Bill Knott and Ralph Prince of NASA Kennedy, Peggy Evanich of NASA Headquarters, Hatice Cullingford, Michael Duke, Walter Guy, Albert Behrend, Cinda Chullen, and Donald Henninger from NASA Johnson, and Peter Kujawski and John Schelkopf of General Electric. A number of additional guests visited individual researchers during a two-day CELSS Conference at Texas A&M.

Travel for discussions with others included:

Oran Nicks - visited Boeing in Seattle to discuss research

Tom Rogers, Bob Murray and George Peterson - NASA Kennedy Space Center, to attend meeting of American Institute of Biological Sciences Panel.

Tom Rogers - visit to Lockheed at NASA Johnson Space Center to discuss research

Oran Nicks - two visits to Prairie View A&M University briefings on the SERC proposal and for planning their role in the proposal

Oran Nicks, Jim Holste, Gloria Johnson - visited NASA Johnson Space Center and discussed life support systems research with several people, including Technical Monitor Hatice Cullingford

Frank Little - attended NASA conference and workshop on modeling at San Diego

Mark Holtzapple - presented paper at AI ChE in New Orleans

Jim Holste, Frank Little, Tom Rogers and Oran Nicks - visited NASA Johnson to discuss life support system research plans

Frank Little, Peter Sharpe - visited NASA Johnson to discuss final report with Hatice Cullingford, and to present results of modeling studies.

Highlights - Activities

The RECON team organized ceremonies officially dedicating the RECON Laboratory on November 13. During this ceremony, Peter Kujawski and John Schelkopf, officials from GE, were formally recognized and thanked for their donation of the GE built Integrated Waste Management-Water System, known as the RITE System. This equipment had been built and system tested in the 1970's as a functioning prototype of a space station system capable of water recovery and waste processing for a four person crew. The equipment provides a starting capability for upgrading mechanical and chemical systems, and for enhancing early integration experiments incorporating biological processes.

The ceremony was well attended by University and NASA officials. Frank Borman, a former astronaut, was a special visitor at the laboratory dedication.

Bob Murray, who was Project Manager at General Electric Co., when the GE water and waste management system was developed, joined the team as an Adjunct Research Engineer of the Texas Engineering Experiment Station. He has been actively involved in the installation and refurbishment of the system in the RECON Lab, and has contributed greatly to the group research activities. During this reporting period, the RECON group developed and submitted an unsolicited proposal for a NASA sponsored Space Engineering Research Center for Regenerative Life Support Systems. The center proposal team was headed by Jim Holste, Peter Sharpe, and Oran Nicks of TAMU and Kamel Fotouh of Prairie View A&M University.

A two-day Conference on Controlled Environmental Life Support Systems Research was hosted at Texas A&M University during this grant period by the Space Research Center. (See information in the

Appendix). Papers were presented by a variety of speakers from NASA, industries, and universities, and by members of the RECON Team. Sharing results and experiences with others working in the field provided very useful information and established contacts for further coordination.

Dr. Frank Little participated in a three-day NASA sponsored conference on Modeling for Life Support Systems. This conference included a workshop activity that addressed plans for future modeling efforts. The modeling that the RECON team has been doing appears to be appropriate as a contribution to the mainstream effort.

Report Organization

This report contains sections on modeling, experimental activities during this grant period, and topics under consideration for the future. The sections contain discussions of:

1. Four concurrent modeling approaches that were being integrated near the end of this reporting period; 1) Knowledge-based modeling support infrastructure and data base management, 2) Object-oriented steady state simulations for three concepts, 3) Steady state mass-balance engineering tradeoff studies, and 4) Object-oriented time-step, quasidynamic simulations of generic concepts. These are being combined to provide an integrated modeling capability during the next phase of team activities.

2. Interdisciplinary research activities, beginning with a discussion of the RECON lab development and use, and followed with discussions of waste processing research, algae studies and subsystem modeling, low pressure growth testing of plants, subsystem modeling of plants, control of plant growth using lighting and CO₂ supply as variables, search for and development of lunar soil simulants, preliminary design parameters for a lunar base life support system, and research considerations for food processing in space.

3. Appendix materials, including a discussion of the CELSS Conference, detailed analytical equations for mass-balance modeling, plant modeling equations, and parametric data on existing life support systems for use in modeling.

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SECTION II

MODELING

Chapter 1

RECON SYSTEMS DESIGN AND MODELING TOOLS ACHIEVEMENTS

Prepared by

R. Mayer

P. Mayer

S. Wells

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**Industrial Engineering
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Chapter 1

RECON SYSTEMS DESIGN AND MODELING TOOLS ACHIEVEMENTS

The development of systems engineering and modeling tools represented one of the major thrusts of this funding period. This systems design and analysis tool development can provide the following benefits:

1. Provide a communication medium for linking activities at all levels and among all disciplines within the RECON design group.
2. Provide a means of evolving the RECON system design through use of a knowledge based design configuration generation capability.
3. Provide an integration template for identifying necessary processes for ecological closure. For example, ammonia synthesis was identified as a missing component. As a result, work was initiated on the design of a miniaturized ammonia synthesizer.
4. Provide software systems which can be used for short term studies of closure and equipment sizing, as well as analysis of control schemes, bottleneck analysis, queuing problems and failure analysis. These tasks have also been initiated.
5. Provide tools for qualitative analysis of system design concepts. These tools can provide first principles reasoning for defining system requirements and design conceptualization. They can be used for evaluation of fuzzy knowledge.
6. Provide a program environment for the management of:

- (a) Changing requirements
- (b) Evolving design
- (c) Systems simulation models
- (d) Experimental and prototype testing.

This program environment software can control and expedite the whole project. It is particularly useful for situations where distributed systems span many components.

ENGINEERING PROCEDURES IN EVALUATING ALTERNATE CELSS CONFIGURATIONS

To appreciate the significance of the software tools to support CELSS design which have been developed to date, it is useful to review the steps that are necessary to develop and evaluate CELSS system configurations. The procedures for developing engineering design for complex, poorly defined systems can be classified into six steps.

Define System Requirements

The first step in the system development process is to identify the needs, constraints, and processes required to establish and maintain a four man colony on the moon. Given a space mission definition, the needs represent necessary functions which the system must perform or conditions which the system must adhere to. Requirements on the other hand, are limiting conditions on the needs. Thus, for example, there is a need to recover nitrogen, the requirements specify how much, in what form, and from what form. The previous section of this report described the mission scenario and basic needs we are addressing with the RECON system. However, these needs, and certainly the requirements formulated against these needs will change throughout the life of the RECON program. Thus, a system for managing this evolution is required. Because of the size, complexity, and breadth of technology inherent in a RECON system, we have used several systems engineering methods for actually developing the needs and requirements (principally a function modeling technique). As these models will require updating and maintenance through the life of the RECON effort, we have developed automated support tools for the development, management, and integration of these requirements development methods.

Survey Alternate Configurations

Given criteria that identify the system requirements, determination of what subsystems are necessary, and how can these subsystems be interfaced becomes the next step. Critical decisions in this step include determination of how the systems requirements are to be allocated to specific subsystems and interfaces? More than one potential answer to this question is both possible and feasible in most cases. Alternatives need to be described and represented in a format facilitating selection of the most appropriate configuration. The processes, components and linkages that were identified in the initial RECON design are shown in Figure 1.1. This design can evolve through the identification of:

1. Different technologies for the components.
2. Different organizations of the components into subsystems.
3. Different interfacing and control structures.

As the alternative configurations are surfaced (either by the systems design team or by the individual component technology researchers) they must be:

1. Evaluated for consistency with the requirements.
2. Evaluated for consistency with the design configuration.
3. Modeled and analyzed for performance.

Characterize Component Technologies

Once the structure of the overall system has been configured, the next issue to be addressed in the development process is the determination of what technologies are available to realize the components, interfaces, and structure of that system. A survey of available technologies from the literature and technical experts is one of the first steps in this procedure. From this background information, the requirements of the individual technologies and the behavior and performance of the different components is determined. The behavior and performance of different component technologies is defined in terms of mathematical rate equations and conservation of mass and energy flows. Specific aspects to be addressed include weights, volumes (internal and external), input-output composition, reaction and flow rates, power consumption, dynamic properties, operating temperatures, pressures, reliability, heat generation, and cooling demands.

Detailed Design Configuration

This step involves the development of specific systems configurations in which the logical system components are matched to technology capabilities. At the same time, component technology constraints are matched to the system environment. This includes meeting the needs of one component from other system components. This configuration development activity is one of the most complex procedures in the development of a complex integrated system such as RECON. Our particular situation is complicated by the inclusion of biological based technologies along with chemical, mechanical, and electrical systems. Thus, for example, two very different detailed design configurations could result from the same logical design configuration by choice of a biological technology component in the one case and the choice of a chemical based component in the other.

Engineering Analysis

The engineering analysis procedure begins with decisions on what questions must be answered or hypotheses which must be investigated. In what ways can the configuration design be evaluated and tested? What are the critical features that must be brought into focus during the analysis phase? In systems such as CELSS, one of the critical classes of questions has to do with the determination of engineering

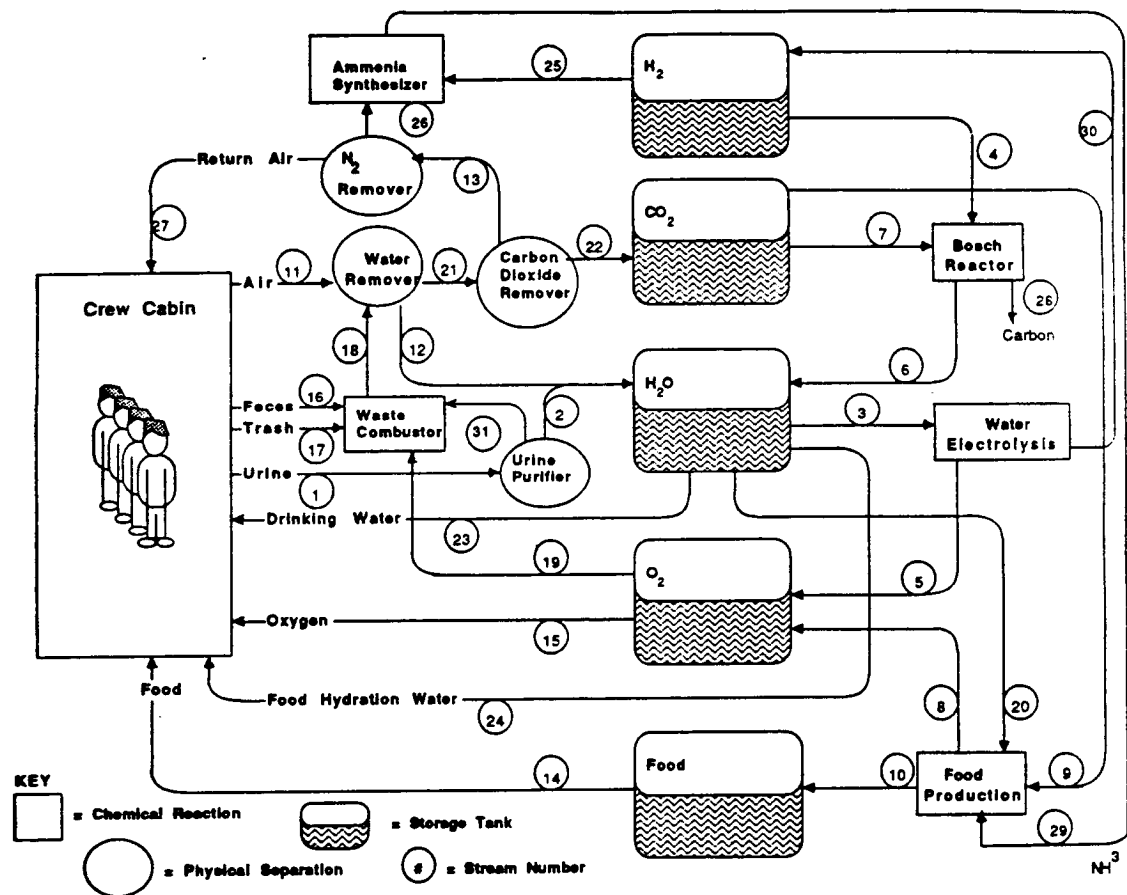


Figure 1. CELSS schematic using algae for food and oxygen production.

Figure 1.1: CELSS schematic using algae for food and oxygen production

parameters for system configuration. Often as much effort is expended in the determination of these critical engineering variables as in the use of the variables to detail or validate a specific design. Models must then be formulated that are appropriate for testing these concepts. The resulting models must be parameterized and solution algorithms for sets of mathematical equations implemented. The performance output from the computer solutions must then be analyzed in terms of the original hypotheses.

Design Modification and Failure Analysis

From the results of the previous analyses, steps are taken to identify the limiting technology inherent in different systems configuration. For example, in our study, the ammonia synthesizer was identified as a limiting technology. A design for a prototype synthesizer was developed and new system configurations were formulated. Failure analysis and the need for redundancy and alternate back-up technologies can also be initiated at this phase of the project. This iterative process is where the bulk of the design development time is spent. As we have experienced with the initial RECON project, the design evolves at an uneven rate. Breakthroughs or knowledge in one area allows that area to be detailed quickly where as others develop at a later time. Items identified as simple components in the initial logical design end up containing enough substructure to be considered as subsystems. Most importantly, the implications of technology alternatives in one subsystem or component can ripple through the entire design, simplifying some areas and causing additional complexity in others. Maintaining control of the design evolution, assessing changes in requirements, and ensuring accuracy in the modeling / analysis of a configuration becomes critical in this stage of the design evolution.

It is important to note that the modeling / analysis / experimentation systems also are undergoing evolution during this time period. Analytic models become refined as better approaches are recognized or more powerful model analysis tools are available. As the data coming back to the designers is evaluated, they identify additional needs for analysis. As the modeling activities attempt to address those needs, they generate additional requirements for experimental data. It begins to be a non-trivial task just to determine what models in what combinations with which data sets can be used on a particular design configuration to produce the desired analysis results. In a large, integrated system such as RECON, these needs demand intelligent software support or the costs begin to rise exponentially, and the quality drops dramatically to the point where the only option is to build one and fly it.

FACILITATING IMPROVED CELSS CONFIGURATIONS WITH INTELLIGENT DESIGN SUPPORT SOFTWARE

Traditional approaches to systems design is currently undergoing a revolution with the development of computer software systems that rapidly speed the development of new designs. The goal of these software systems is to make systems design easier and more efficient for rapid development of design concepts, modifications, and analysis of their limitations or strengths. These software techniques can be used to program design support environments which include intelligent capabilities which

can both assist in the generation of design configurations as well as help to ensure completeness and consistency of proposed designs. They can provide an affordable mechanism for design configuration management. This feature is especially important where design configuration and design analysis information is being generated by a large group of researchers. These intelligent support environments can provide a powerful design experience capture capability to accurately and usefully record the experience of the research group. Such a capability is particularly important to NASA in situations where the resulting (research developed) design will be required by aerospace companies under contract to build CELSS configurations. The software systems provide an electronic capture of the experience and rationale of the originators of the design. The design experience can be internally documented to provide a rationale for design steps including a historical record of trade-off criteria for the benefit of both NASA and aerospace contractors.

Object Orientation in Design Support Systems

The use of object oriented programming techniques provides a template for the development and modification of regenerative closed life support systems configurations. This approach integrates and speeds design configuration and establishes a framework for rapid modifications and improvements. For the design engineer, it provides a design environment that enables the problem to be structured in a way compatible with the development of sequentially improved physical prototypes. The computer environment enables prototype designs for components and system configurations to be visualized rapidly on the screen. Modifications can be rapidly implemented. Additional decision and management features can be added in terms of expert rules or experience.

Justification

The use of existing software design tools and the development of new tools are justified because CELSS installations represent a large investment of expertise and time from a wide range of different disciplines that have not previously been partners in design. We refer specifically to the bringing together of aerospace engineers and biologists. A computer software system with the capability of explicit representation of both physical and biological systems can provide a means of unambiguous communication. Graphics combined with window displays of critical numerical values provide a means for concept development and testing that couples ease and elegance.

In addition, explicit representation of physical components provides the researchers with a means for the different disciplines to reason together and comprehend how different components respond with the system constraints encountered on the moon.

SYSTEMS DESIGN AND MODELING ACHIEVEMENTS

Recognizing that the CELSS concept is a long-term undertaking, development of systems design and modeling tools was undertaken at four levels.

These four levels were:

1. Intelligent Design Support Environments
2. Qualitative reasoning support for the design process

3. Smart user interfaces to traditional steady state design analysis models.
4. Simulation modeling.

The four complementary approaches have different time spans for development and meet the needs of the CELSS project at different phases of its development.

Each of the above software tools have been implemented using object oriented programming methods. They are implemented on Symbolics computers using GENERA 7.1 Dynamic windows and presentation objects. All codes are developed in Common Lisp using either LISP FLAVORS or KEE 3.1 (which is a higher level implementation of an object oriented programming paradigm). Thus, an attempt has been made both to satisfy near term CELSS requirements for design support and modeling process automation and to develop to support integration of the individual efforts into the IDSE within a common framework.

The interdependence and overlaps among the three modeling approaches are shown schematically in Figure 1.2. The purposes and strengths of each of the modeling techniques are shown in Figure 1.3.

The following subsections briefly describe each of these areas. In the sections following this section we describe our progress in prototyping tools in three of these areas.

Intelligent Design Support Environment Development

One of the primary activities during this effort in the area of software tools has been the conceptualization of an integrated environment for intelligent support of the design process outlined above. The work in this area is building off of ongoing programs in the Industrial Engineering Departments' Knowledge Based Systems Laboratory at Texas A&M under Air Force and NASA sponsorship.

The automated environment needed to support the application of the design procedures and methods described above and to maintain the evolving system description can be described as an Intelligent Development Support Environment (IDSE) (see Figure 1.4). The purpose for prepending the term "Intelligent" is to recognize that the evolving definitions and models supported by this environment represent a knowledge base of the design process, as well as to recognize the fact that a large number of the applications developed will be of the expert system (or at least knowledge based system) variety. The computerized environment and tools contained therein will eventually cover all of the activities from strategic planning through maintenance of the evolving information system. The architecture for such a system is illustrated in Figure 1.5. As can be seen from this figure, the IDSE concept uses a structure very similar to that of an integrated information system of the corporation only on a reduced scale. The utilities contained in the "Computerized System Development Environment" (SDE) component of the IDSE include:

1. Life cycle artifact management (maintenance of the evolving system description).
2. Configuration management utilities.

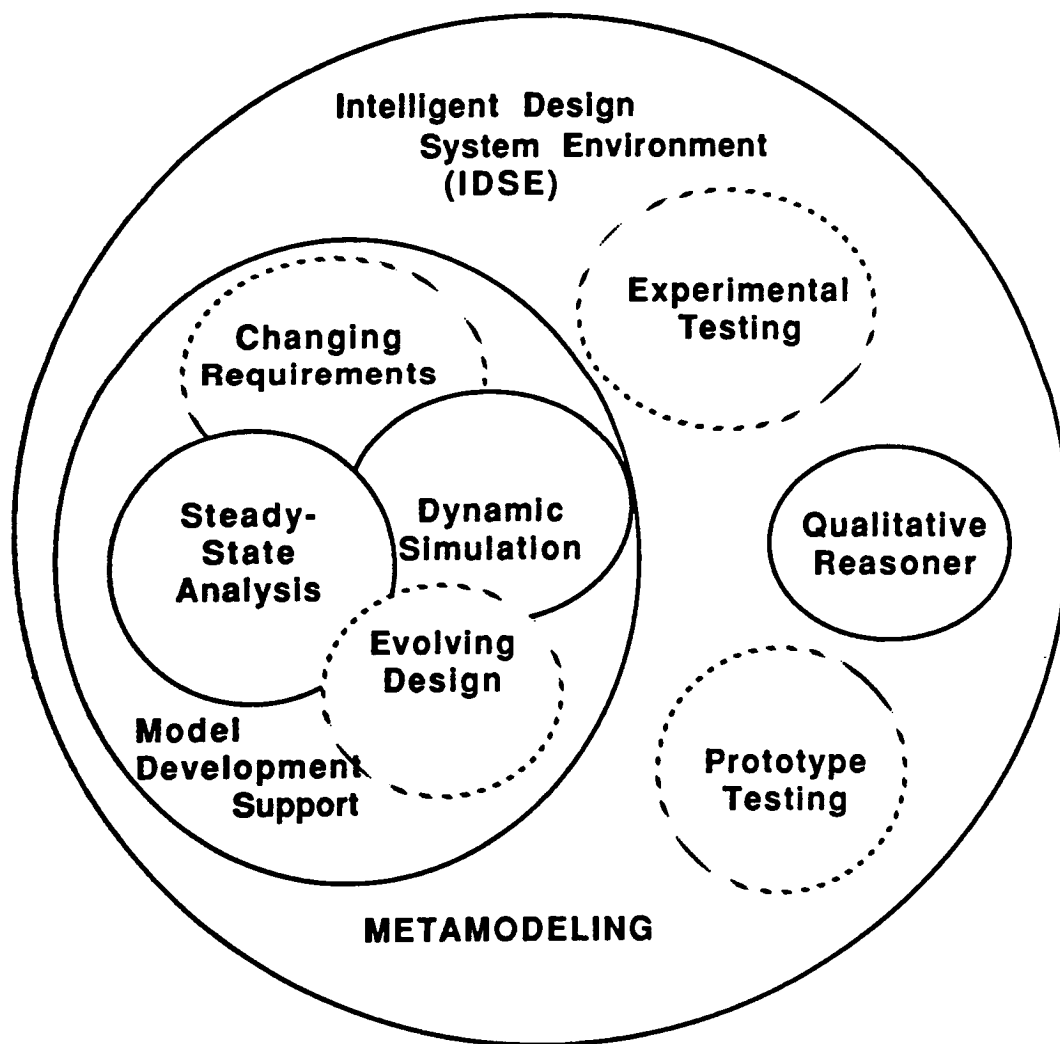


Figure 1.2: Interaction of the IDSE, SSM, & DM

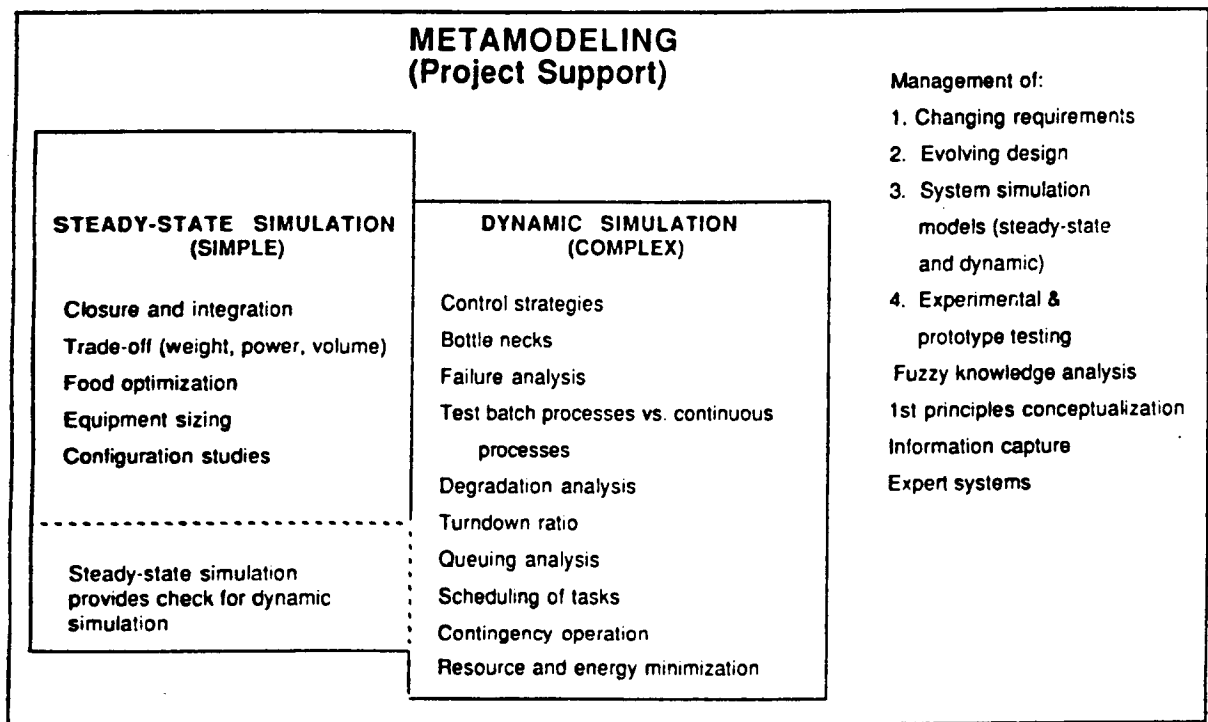


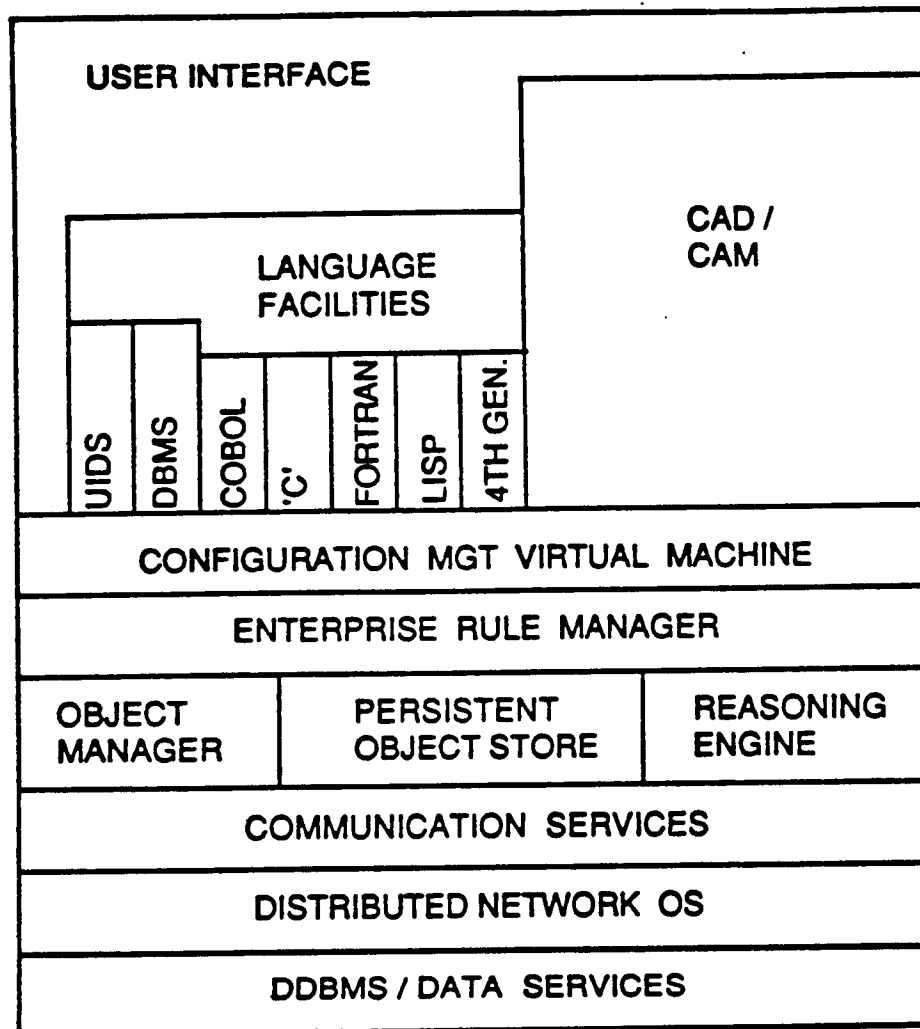
Figure 1.3: Comparisons of Model Type Application Areas

3. Inter-, and intra-model integration support.
4. Document generation support.
5. Knowledge / system design description data acquisition support.
6. Model development support.
7. Qualitative analysis of system designs and analysis results.
8. Heterogeneous development hardware support (micro, mini, mainframe, and workstation support).
9. Networking to allow enhanced communication within the research team.
10. Window and graphics user interface development support.
11. Common user interface style for all tools.
12. User profiling and usage scenario support to minimize user exposure to system complexity.
13. On-line documentation.
14. Tutoring support.

Of these SDE capabilities the requirements, design, models, test, and analysis data integration, configuration management, and control are some of the most important needs of a large scale system development such as CELSS. The problems of engineering data management which must be address by the eventual IDSE include:

1. Engineering change control
2. Data access
3. Data tracking
4. Product configuration management
5. Data release control
6. Engineering change process facilitation

The IDSE, originally conceived for aerospace engineering and manufacturing systems, is being adapted for CELSS applications. The initial effort has focused on establishment of an integrated modeling support environment. The prototype tools developed in this area have focused around requirements engineering methods, specifically the IDEF methods. IDEF is being used for automobile manufacturing, Air Force and Navy applications, and has great potential use in the design phase of CELSS configurations. IDEF stands for Integrated Computer-Aided Manufacturing Definition Language. It provides a technique for defining requirements and design concepts for large scale integrated systems. The current prototype tool supports



EVOLVING SYSTEMS ARCHITECTURE

Figure 1.4: IDSE Concept

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Architectural View of the IDSE

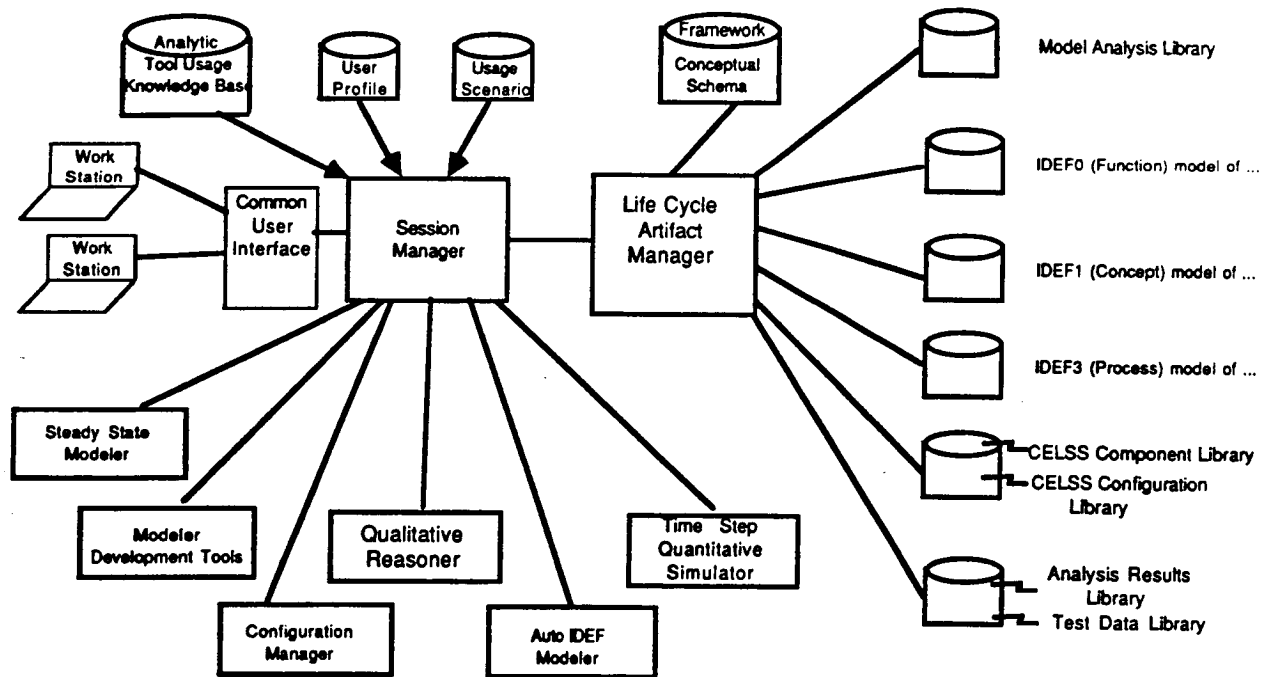


Figure 1.5: IDSE Architecture

both IDEF0 (a hierarchical system function modeling technique) and IDEF1 (a network concept modeling technique). These methods were chosen as the focus of the initial prototype because of their importance to the definition and design of CELSS type systems. They are also required to complete the development of the IDSE concept.

The description acquisition framework established to support these modeling tools was determined to be the first step required to verify the system architecture. It provides the platform for development of the qualitative reasoning support tools required to provide actual engineering thought process support.

Qualitative Reasoning Support for the Design Process

The design activities described in the previous section of this report can be synopsized as a process of making judgements or educated guesses followed by model building and analysis followed by revision of the initial decisions based on the information acquired through the analysis and test process.

The importance of this form of deductive simulation extends beyond the realm of improved management and design decision making. To be successful (as well as safe), the complex space systems of the future must have the capability to fall back on a knowledge base of reasoning capabilities which include domain common sense, qualitative, and causal reasoning methods. They must be capable of understanding how unplanned behavior comes about and the limitations of the resources they have control for responding to those situations. This kind of capability requires the representation and manipulation of qualitative information about the physical and organizational systems within their perview. The concepts, formalizations, and methods investigated in the course of this research can be directly applied to the provision of these types of capabilities in future CELSS systems.

Related work along the lines of this approach from which we will be developing the CELSS qualitative design analyzer includes:

1. Qualitative Simulation of Manufacturing systems [Mayer 86]
2. Generation of Qualitative Models from System Descriptions [Mayer 87]
3. Causal Reasoning about Manufacturing System Designs [Mayer 88]
4. Causal Model Based Machine Fault Diagnosis Shell [Krishnamurthi & Mayer 87]
5. Cooling System Designer [Friel & Mayer 87]
6. Causal reasoning (e.g., qualitative physics [DeKleer and Brown 84, Kuipers 84])
7. Common sense reasoning about physical systems (e.g., naive physics [Hayes 79, Hobbs 87])
8. Continuous process qualitative reasoning (e.g., qualitative process theory [Forbus 84, Kuipers 86])

9. Planning and mechanical system design (e.g., reasoning about plans [McDermott 86]; common sense planning and understanding [Wilensky 83])
10. General theory of natural language semantics (e.g., based on situated agents [Barwise 85] for continuous concepts [Bunt 85])

Each of these works addresses the problem of common sense reasoning about the causal and qualitative aspects of system structure and dynamics from either natural language descriptions of the system or from common sense models of those systems. The work by Bunt, Hayes, and Barwise focuses primarily on representational issues, while the work by McDermott and Wilensky focuses on the planning issues which we found were required for generation of qualitative models from the descriptions. Finally, the work by DeKleer, Forbus, and Kuipers addresses the problem of reasoning with qualitative models formed from these representations. The work by Friel focused on the combined use of rule based design generation with qualitative analysis for the generated designs.

Steady-State Process Modeling (SSM)

The activities in this area are aimed at providing methods for evaluating designed components and configurations using steady state analysis techniques. The tools under development support interactive configuration of the design options identified by the engineering team, specifically, the options of food resupply, algae only food production, and diverse higher plant-algae food production systems. The current tool supports not only the evaluation of a single value for a design parameter but also range and factored analysis. Figure 1.6 displays the basic interface for the current CELSS steady state modeler with a graphic summary of a range evaluation for the percentage of algae in the crew diet.

System Dynamics Modeler (DM)

In addition to the support of the design evolution process and the steady state modeling, there is a need to support analysis of the dynamic behavior of a proposed CELSS configuration. A prototype modeler providing a time step based simulation analysis capability has been developed. The use of this capability will become important as the CELSS configuration becomes more clearly defined. This modeler has been designed in such a way that it can draw on the repository of knowledge about component decisions and specifications managed by the IDSE. It also provides a means for testing for queuing problems, storage insufficiencies, and dynamics of component control and response delays.

SMART INTERFACES FOR STEADY-STATE PROCESS MODELING

A steady-state process model was developed for the CELSS configuration shown in Figure 1.0. An analyzer for this model was implemented in BASIC, with preliminary numerical calculations presented in the December progress report. An intelligent interface was designed for steady state models. This interface has been implemented in LISP & FLAVORS on the Symbolics. The numerical calculations of the LISP code have been checked against the BASIC code and agreement verified. The steady state models have been further refined to include the six higher plants

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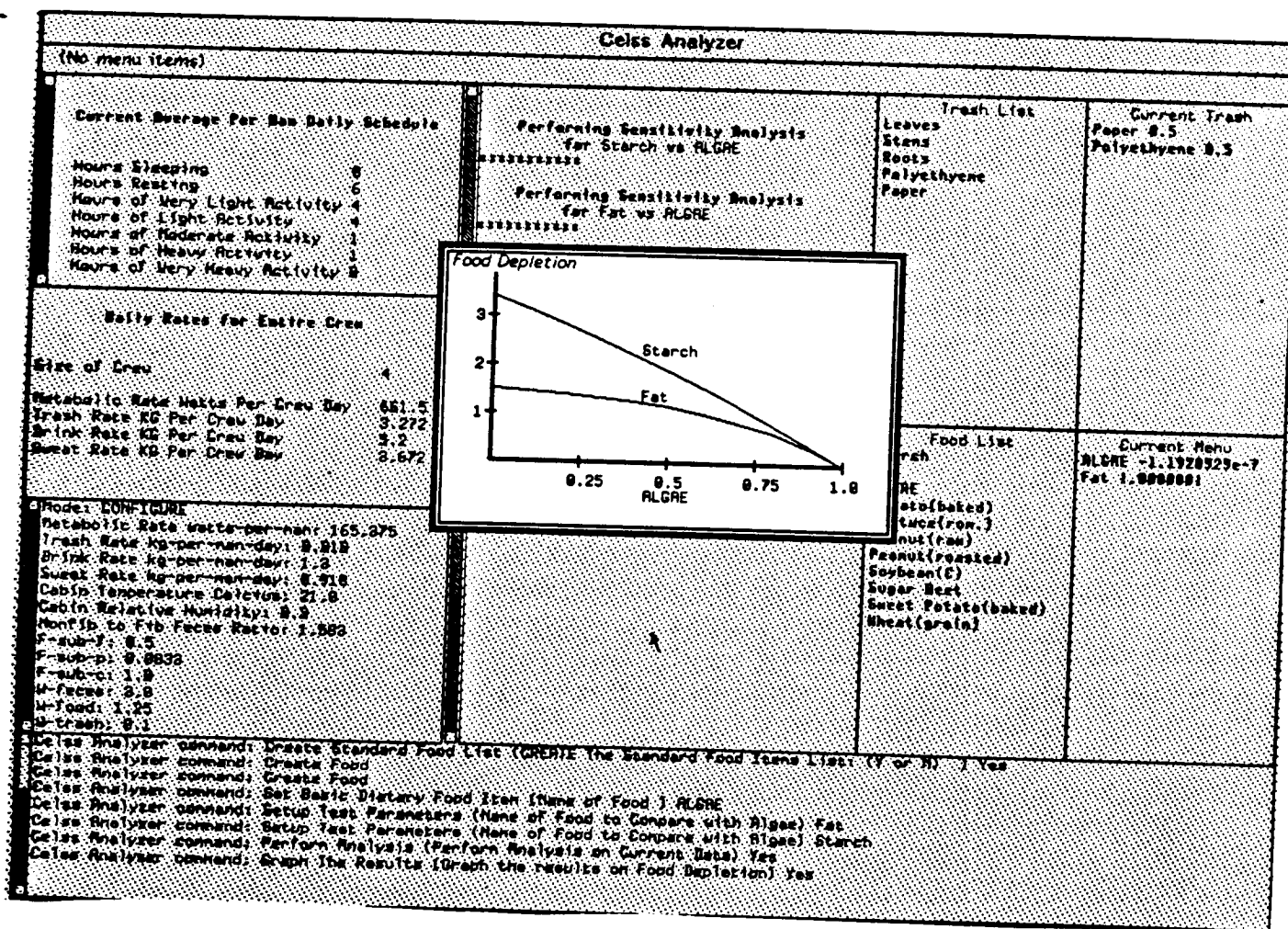


Figure 1.6: Interactive Steady State Process Modeler

on the NASA list of approved plants. The two versions of the analyzer in BASIC and LISP FLAVORS were again verified that calculations gave the same values.

A demonstration of the input screen of Presentation Objects based steady-state process model interface is shown in Figure 1.7. The daily schedule of activities is shown in the upper left window. Daily rates and crew size are shown in mid-left window and input parameters for the steady-state simulation are shown in the lower left window. The possible trash list is shown in upper right with the potential food sources shown in lower right. The current trash and food menu are shown in the far right windows. Note that some foods can exist in uncooked or cooked form.

A typical simulation is shown in Figure 1.8. A crew size of four has been chosen. The current trash is polypropylene and paper. The food is a miserable diet of algae and fat. The calculations do show that astronauts can survive and live on such a diet and that they will eat 2.44kg dry food per day. This interface allows the engineer to easily set up a configuration for analysis. The interface guarantees that the configuration is consistent with the underlying steady state model assumptions. The interface automatically prepares the data for the analysis routine, summarizes the results and supports range testing.

TIME STEP SIMULATION TECHNIQUE

The ultimate goal of producing a truly dynamic model was well beyond the available resources of both time and personnel. However the need for a time step simulation to test the dynamics of the life support system with respect to examining different operating scenarios, as well as determining the response of the system to transient unusual demands (failure analysis) led to the implementation of a time step simulation, in which the length of the time step is sufficiently short compared to the response time of the system components that a quasi steady-state may be assumed for the duration of the interval for which the mass balance equations of the system are sequentially solved. The resulting output then forms the initial conditions for the next psuedo-dynamic time step.

Development of this psuedo-dynamic simulation also required a much greater knowledge of an a more finely detailed model for the individual components which comprise the system that are necessary for the true steady-state simulation case described above. This requirement was extended to the biological components (crew members as well as algae and plants) in addition to the individual physio-chemical life support system components. Due in part to time and personnel constraints, and in part to lack of detailed knowledge, compromises were made in the modeled representation of the individual system components (this is particularly true for the biological, e.g., food plant, components). Activity schedules were assigned to the four individual crew members and a food menu developed for each of the three general scenarios: completely external food resupply; growth of algae for food; and an astronaut grown higher plant food source.

The time step simulation development has proceeded parallel to the steady-state model development. The program was written under the Intellicorp Knowledge Engineering Environment 3.0 object-oriented knowledge base shell on a Symbolics

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Celss Analyzer			
(No menu items)			
Current Average Per Man Daily Schedule Hours Sleeping 8 Hours Resting 4 Hours of Very Light Activity 6 Hours of Light Activity 3 Hours of Moderate Activity 2 Hours of Heavy Activity 1 Hours of Very Heavy Activity 0	STATUS OF REACTORS WASTE COMBUSTOR (kg dry matter/day) 3.8854702 BOSCH REACTOR (kg CO ₂ /day) 9.839116 ELECTROLYZER (kg O ₂ /day) 10.922248 ALGAE PRODUCTION (kg dry alge/day) 1.2239174 AMMONIA SYNTHESIZER (kg N ₃ /day) 0.15543751	Trash List Leaves Stems Roots Polyethylene Paper	Current Trash Paper 0.5 Polyethylene 0.5
Daily Rates for Entire Crew Size of Crew 4 Metabolic Rate Watts Per Crew Day 695.666 Trash Rate KG Per Crew Day 3.272 Drink Rate KG Per Crew Day 5.2 Sweat Rate KG Per Crew Day 3.672	STATUS OF STORAGE TANKS HYDROGEN ACCUMULATION (kg H ₂ /day) 0.516993 CARBON DIOXIDE ACCUMULATION (kg/day) 1.8718767 WATER ACCUMULATION (kg/day) 0.0 OXYGEN ACCUMULATION (kg/day) 0 (controlled for this) FOOD DEPLETION (kg dry food/day) 1.2239174 POTENTIAL OXYGEN (kg/ O ₂ /day) 1.3614159	Food List Starch Fat ALGAE Potato(baked) Lettuce(raw.) Peanut(raw) Peanut(roasted) Soybean(C) Sugar Beet Sweet Potato(baked) Wheat(grain)	Current Menu Fat 0.5 ALGAE 0.5
Mode: CONFIGURE Metabolic Rate watts-per-man: 173.91667 Trash Rate kg-per-man-day: 0.818 Drink Rate kg-per-man-day: 1.3 Sweat Rate kg-per-man-day: 0.918 Cabin Temperature Celcius: 21.0 Cabin Relative Humidity: 0.3 Nonfib to Fib Feces Ratio: 1.583 F-sub-f: 0.5 F-sub-p: 0.8833 F-sub-c: 1.0 W-feces: 3.0 W-food: 1.25 W-trash: 0.1			
Celss Analyzer command: Change Crew Size (Enter the Number of Crew Members) 4 Celss Analyzer command: Select Daily Activities Schedule Celss Analyzer command: Create Standard Trash List (CREATE The Standard Trash Items List: (Y or N)) Yes Celss Analyzer command: Create Waste Item (Type of Trash) Polyethylene (Percentage of Trash Type in Waste) .5 Celss Analyzer command: Create Waste Item (Type of Trash) Paper (Percentage of Trash Type in Waste) .5 Celss Analyzer command: Perform Analysis (Perform Analysis on Current Data) Yes Celss Analyzer command: Create Menu Item (Name of Food) ALGAE (Percentage of Food in Diet) .5 Celss Analyzer command: Create Menu Item (Name of Food) Fat (Percentage of Food in Diet) .5 Celss Analyzer command: Perform Analysis Yes Celss Analyzer command:			
To see other commands, press Shift, Control, Meta-Shift, or Super. [Fri 25 Mar 11:02:34] steve CL-USER: User Input			

Figure 1.7: CELSS Steady State Modeler Interface

Celss Analyzer			
(No menu items)			
Current Average Per Man Daily Schedule Hours Sleeping 8 Hours Resting 4 Hours of Very Light Activity 6 Hours of Light Activity 3 Hours of Moderate Activity 2 Hours of Heavy Activity 1 Hours of Very Heavy Activity 0	CELSS ANALYZER RESULTS STATUS OF HUMANS Crew Size 4 FOOD CONSUMPTION (kg dry food/day) 2.4478347 FECEs PRODUCTION (kg dry feces/day) 0.34775165 URINE PRODUCTION (kg urine water/day) 0.95672786 UREA PRODUCTION (kg/day) 0.18571845 CARBON DIOXIDE PRODUCTION (kg/day) 4.728565 OXYGEN CONSUMPTION (kg/day) 4.5925927 WATER PRODUCTION (kg/day) 1.7831373 RESPIRATORY QUOTIENT (CO2/O2) 0.74888585	Trash List Leaves Stems Roots Polyethylene Paper	Current Trash Paper 0.5 Polyethylene 0.5
Daily Rates for Entire Crew Size of Crew 4 Metabolic Rate Watts Per Crew Day 695.666 Trash Rate KG Per Crew Day 3.272 Drink Rate KG Per Crew Day 5.2 Sweat Rate KG Per Crew Day 3.672	STATUS OF SEPARATORS WATER REMOVER (kgH2O/day) 12.795763 CARBON DIOXIDE REMOVER (kg CO2/day) 13.382882 URINE PURIFIER (kg urine water/day) 0.95672786 NITROGEN REMOVER (kg N2/day) 0.12888737	Food List Starch Fat ALGAE Potato(baked) Lettuce(raw.) Peanut(raw) Peanut(roasted) Soybean(C) Sugar Beet Sweet Potato(baked) Wheat(grain)	Current Menu Fat 0.5 ALGAE 0.5
Mode: CONFIGURE Metabolic Rate watts-per-man: 173.91667 Trash Rate kg-per-man-day: 0.818 Drink Rate kg-per-man-day: 1.3 Sweat Rate kg-per-man-day: 0.918 Cabin Temperature Celcius: 21.0 Cabin Relative Humidity: 0.3 Nonfib to Fib Feces Ratio: 1.583 F-sub-f: 0.5 F-sub-p: 0.8833 F-sub-c: 1.0 M-feces: 3.0 M-food: 1.25 M-trash: 0.1			
Celss Analyzer command: Change Crew Size (Enter the Number of Crew Members) 4 Celss Analyzer command: Select Daily Activities Schedule Celss Analyzer command: Create Standard Trash List (CREATE The Standard Trash Items List: (Y or N)) Yes Celss Analyzer command: Create Waste Item (Type of Trash) Polyethylene (Percentage of Trash Type in Waste) .5 Celss Analyzer command: Create Waste Item (Type of Trash) Paper (Percentage of Trash Type in Waste) .5 Celss Analyzer command: Perform Analysis (Perform Analysis on Current Data) Yes Celss Analyzer command: Create Menu Item (Name of Food) ALGAE (Percentage of Food in Diet) .5 Celss Analyzer command: Create Menu Item (Name of Food) Fat (Percentage of Food in Diet) .5 Celss Analyzer command: Perform Analysis Yes Celss Analyzer command:			
To see other commands, press Shift, Control, Meta-Shift, or Super. (Fri 25 Mar 11:02:08) steve CL-USER: User Input			

Figure 1.8: Configuration Analysis using SSM

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3640 computer. This has results in an interface similar to that described above results are presented in Chapter 3 of this section.

IDSE PROTOTYPE

The work during this phase of the CELSS project on the IDSE concept has included the modification and extension of the integrated model development support component of the IDSE.

The approach taken to the development of the concepts for IDSE combines the traditional systems engineering methods with an approach evolved in the KBS Lab for building knowledge based systems. This approach is heavily oriented towards the use of prototypes and the involvements of domain experts. To this end, a number of different prototypes are constructed in the course of the development activities as displayed in Figure 1.9. In this figure "Feasibility" prototypes refer to prototypes that are constructed largely for *proof of engineering*. That is, prototypes which are constructed to demonstrate that an algorithm or heuristic method can be produced to solve a particular problem. These prototypes are also constructed for the purpose of gathering engineering design data for sizing and design decomposition decisions. "Scenario" prototypes are constructed for requirements development and user interface verification. Scenario prototypes essentially implement a process flow model as described in the previous chapter. They generally offer no "real" functionality, rather only the appearance of functionality.

"Demonstration" prototypes represent the first attempt at putting the functionality of the feasibility prototypes together with the user interface of the scenario prototypes. These prototypes are used primarily for proof of the "systems level" engineering activities. These systems are complete from a "scenario of use" point of view, however, the robustness and the depth of support they provide from a functionality point of view often obviates their use by the domain expert. "Validation" prototypes offer both the breadth and depth of functionality to establish a basis for the domain expert to validate the utility and completeness of the proposed system. Thus, to some extent, the validation prototype is "usable" at least by a select group of users. "Operational" prototypes are robust enough for trial use by the general class of targeted end users. This means that the base functionality is provided along with enough speed and robustness that the average user can experiment with the system. However, there is generally only limited documentation available and little or no training manuals for an operational prototype. Our efforts are focused on the first three types of prototypes with evolution into the fourth area as CELSS needs dictate.

INTEGRATED MODEL DEVELOPMENT SUPPORT ENVIRONMENT

The Integrated Model Development Support Environment is a suite of integrated software tools that provide intelligent support for system modeling. The initial prototypes have focused on support for the IDEF0 and IDEF1 modeling and on the construction of a generalized tool for building such modeler tools called the "Meta-Modeler". The IDEF tools assist in the complete process of function and

PROTOTYPING STYLES

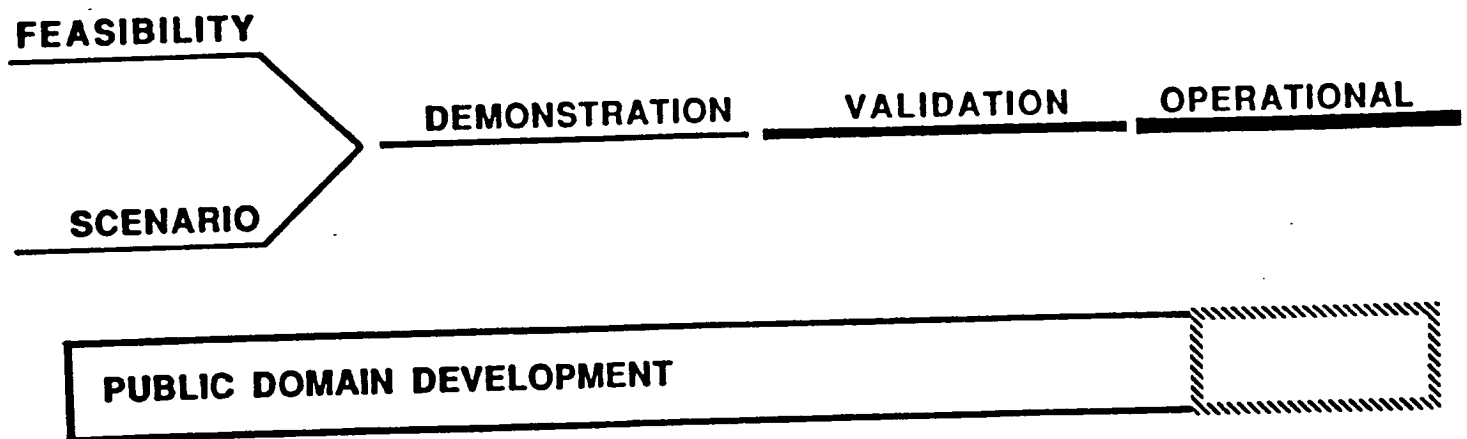


Figure 1.9: Types of Prototyping in the IDSE Development Efforts

information modeling.

Requirements and design modeling begins with the gathering of data about the information to be modeled. This information is accumulated from several sources, one of which would be files of company documentation. Interviews with key individuals in the information trail are also necessary. Group meetings provide another source of information.

The next step in the modeling process is to extract those items that will be the basis of a particular model. For example if the model is to be an IDEF0 model this would be a list of system functions and physical or information objects which relate these functions. For an IDEF1 model this would be a Source Data Item list. Using these lists the data is grouped by topic or other relation. For an IDEF0 model, related activities and functions are grouped together. These groupings will be further refined in the process of describing the logical hierarchical decomposition of the functions of the system. For an IDEF1 model, related information attributes are grouped together. These groupings will be further refined to define the major concept clusters called entity classes. The entity classes are used as the basis for describing relations critical to the operation of the system.

An effective modeler support system must continually check to insure that the model being created obeys the rules of the modeling method. For example, in IDEF1:

1. All entity classes must have unique names.
2. Inheritance of attribute classes and key classes must be insured.
3. In the selection of the attribute classes in a key class, the modeler must populate the key class for each entity class in a unique manner.

An effective modeler support environment must also support the integration of a large number of models being developed either by the same modeler or different modelers. It must also support reuse of existing models. A great deal of the work done by a modeler will involve the integration of a model or a part of a model into another model. This integration is similar to the merging of two models to form a third. The main difference between this and the creation of a model is that in these cases the model elements already exist.

One of the major problems associated with merging or integration of models would be the resolution of conflicts. Often there will two model elements that are the same even though they have different names. For example in IDEF1, the first step in the resolution of these conflicts is to establish a common Attribute class pool and Glossary and a common Entity class pool and Glossary. These are examined to determine which pairs represent the same item.

Modeling Support for IDEF0

A modeling tool for the IDEF0 modeling methodology has been developed to support the management of existing and new IDEF0 models. The tool provides automated support for creating, editing, and storing IDEF0 models. In this section,

a discussion of the requirements for an IDEF0 tool and the design and major features of the prototype IDEF0 tool are presented.

Looking first at an IDEF0 model diagram the component parts (functions) are graphically displayed as boxes. A "function" in IDEF0 describes a decision, action, function, or activity which the system must perform. Interactions between functions are displayed as arrows going into and leaving the box. These arrows represent the inputs, outputs, controls, and mechanisms (ICOM's) associated with the function (see Figure 1.10). The position on a box at which an arrow enters or leaves the box defines the specific relationship between the data associated with that arrow and the function described by the box. For example, in Figure 1.11 the arrow labeled "Control Signals" indicates that the relation between the "Determine Adjustment" function and the "Make Adjustments" function is established by the "Control Signals" object. The IDEF0 method supports a hierarchical organization of the description of the system functions. This feature is useful in both requirements definition, and design representation because it allows the gradual evolution of the details of a functional description (see Figure 1.12).

Two major approaches to building IDEF0 models are in widespread use in government and industry. These approaches are referred to as top-down and bottom-up model building. A goal of the IDEF0 modeling tool is to support both of these construction techniques.

In the top-down IDEF0 modeling approach, the user has the ability to define the purpose, context, and viewpoint of the model and construct the top level A-0 diagram. The activity and ICOM flows are specified for the A0 diagram with respect to this A-0 diagram. Then the user builds the next lower level of the A0 activity by constructing each of the activities in the decomposition. When all activities that make up activity A0 are complete, the ICOM flows are added and checked for consistency with higher levels. The set of activities and flows that comprise the A0 activity are then merged into a diagram that represents the decomposition of the A0 activity. The process then continues by decomposing each the activities in the A0 decomposition (ie., A1, A2, A3, etc.) in the same manner.

The bottom-up approach to IDEF0 modeling begins with the user constructing a node tree to represent the activities of the model. The nodes can then be defined by conversion to activity diagrams. When all activities in a node diagram have been described, ICOM flows are added to create a complete activity diagram. With a subtree complete, the activity descriptions are combined into an activity diagram for the parent node. The parent nodes are then combined with other activity diagrams at the same level by linking them with ICOM flows and combining them to form the description of the next parent node. The bottom-up modeling approach then continues working upward by generalizing activities until the A-0 diagram is created.

The requirements of an IDEF0 modeling tool are to support both types of IDEF0 model construction. Facilities for creating and editing nodes in a node tree, activities in an IDEF0 model, and ICOM flows in an IDEF0 model; merging node and activity descriptions into parent nodes and activity descriptions, respectively; and

Basic IDEF0 Model Components

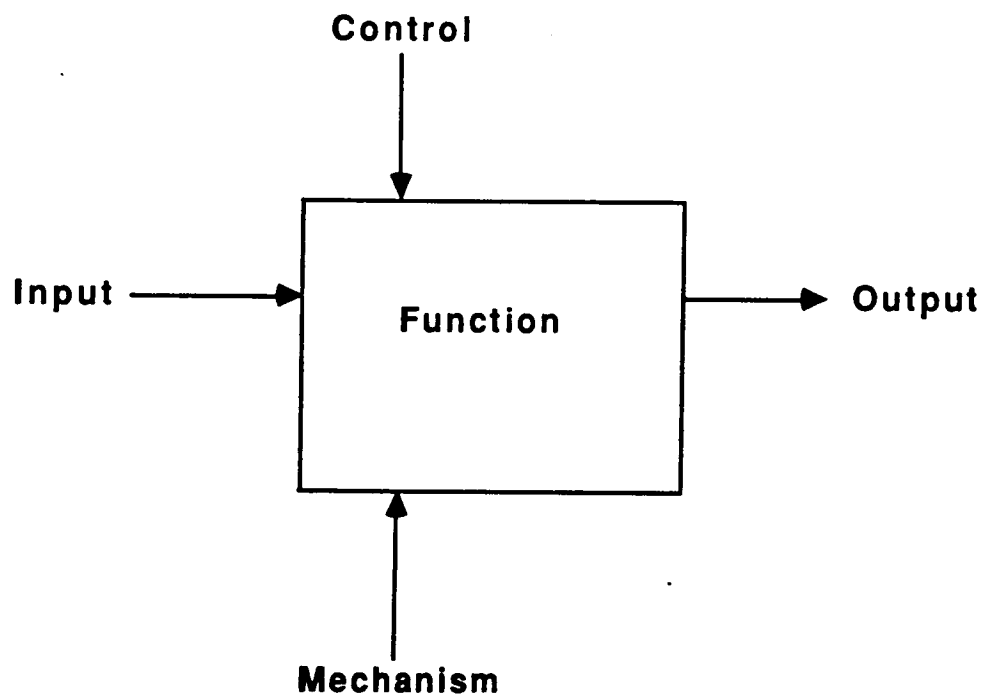
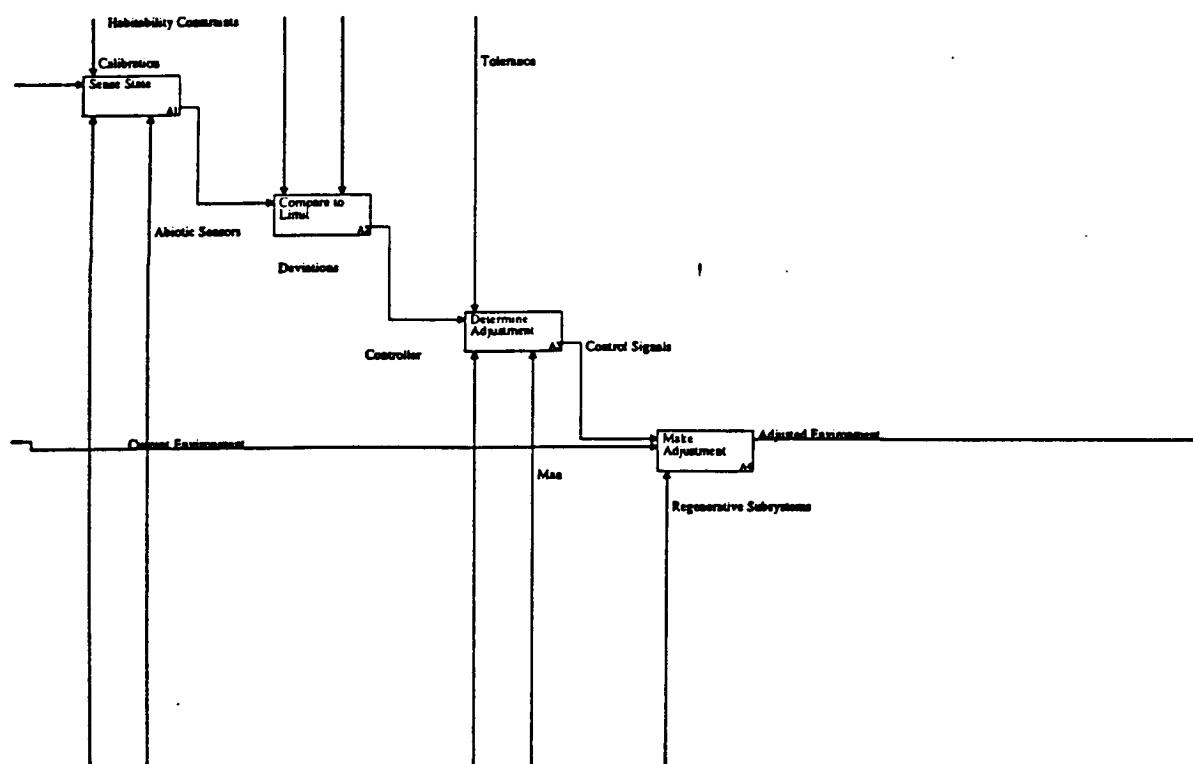


Figure 1.10: Basic Box and Arrow Component Semantics in IDEF0

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	Project:	Rev:	Draft			
	Notes: 1 2 3 4 5 6 7 8 9 10		Recommended			
			Publication			



Node:	Title:	Number:
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Figure 1.11: IDEF0 display of object based relations between functions

IDEF0 Supports Decomposition of Requirements & Design Descriptions

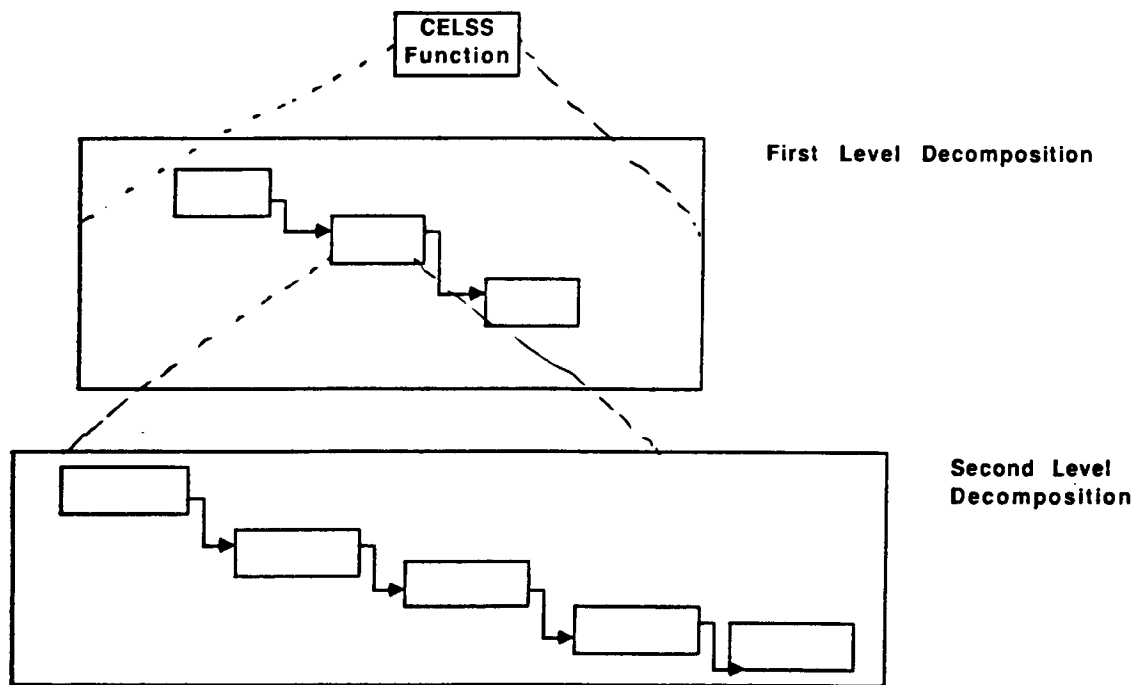


Figure 1.12: IDEF0 hierarchic structure

decomposing nodes and activities must be provided. Additionally, models should be stored to and retrieved from persistent storage and output to hardcopy devices. These requirements are necessary for an automated tool to support IDEF0 model generation and use.

Design of IDEF0 Modeler

The design of the IDEF0 modeler is based upon the Metamodeler concept. The Metamodeler allows a description of the information to be entered and generates the basic functionality necessary for a graphics-oriented tool. An IDEF1 model of IDEF0 was developed to use as input to the Metamodeler. The IDEF1 model developed is shown in Figure 1. An appropriate description was created for the Metamodeler, supplied to the Metamodeler, and the object management portion of the IDEF0 modeling tool was automatically generated.

A major portion of the development of the prototype IDEF0 modeler was directed at development of a cognitive model of an IDEF0 author and design of an intelligent interface based on that cognitive model. The command interpreter, mouse gesture handler, and graphic display were design and constructed to complete the IDEF0 tool. Much of the functionality was intentionally designed to run concurrently with the IDEF1 modeling tool. The user has the ability to operate on models of either modeling methodology with each loaded into the AutoIDEF system at the same time. Figure 1.14 displays the general layout of an IDEF0 modeler screen.

The IDEF0 function modeling tool also supports the following features:

1. Views a system as connected components, where components are functions, connections represent interfaces. This allows description of critical activities and relationships
2. Support the diagrams, text and glossary of IDEF0 fundamental building blocks of diagram - boxes and arrows; each box has four labelled sides: input, output, control, and mechanism.
3. Interconnects boxes and allow hierarchical representation of IDEF0 models.
4. Provides for the development and management of the full model element data dictionary necessary to manage the activity and object definitions which are developed during the modeling process.
5. Supports the model review, integration, and validation process.
6. Provides for cross referencing of diagrams, text, validation results, and glossary information.
7. Provides for the integration of multiple models (up to three at a time).

As the IDEF0 tool is integrated with the IDEF1 tool through the Meta-modeling framework it is possible for the modeler to build such models simultaneously pulling concepts from one to the other. Figure 1.15 illustrates such a dual model session.

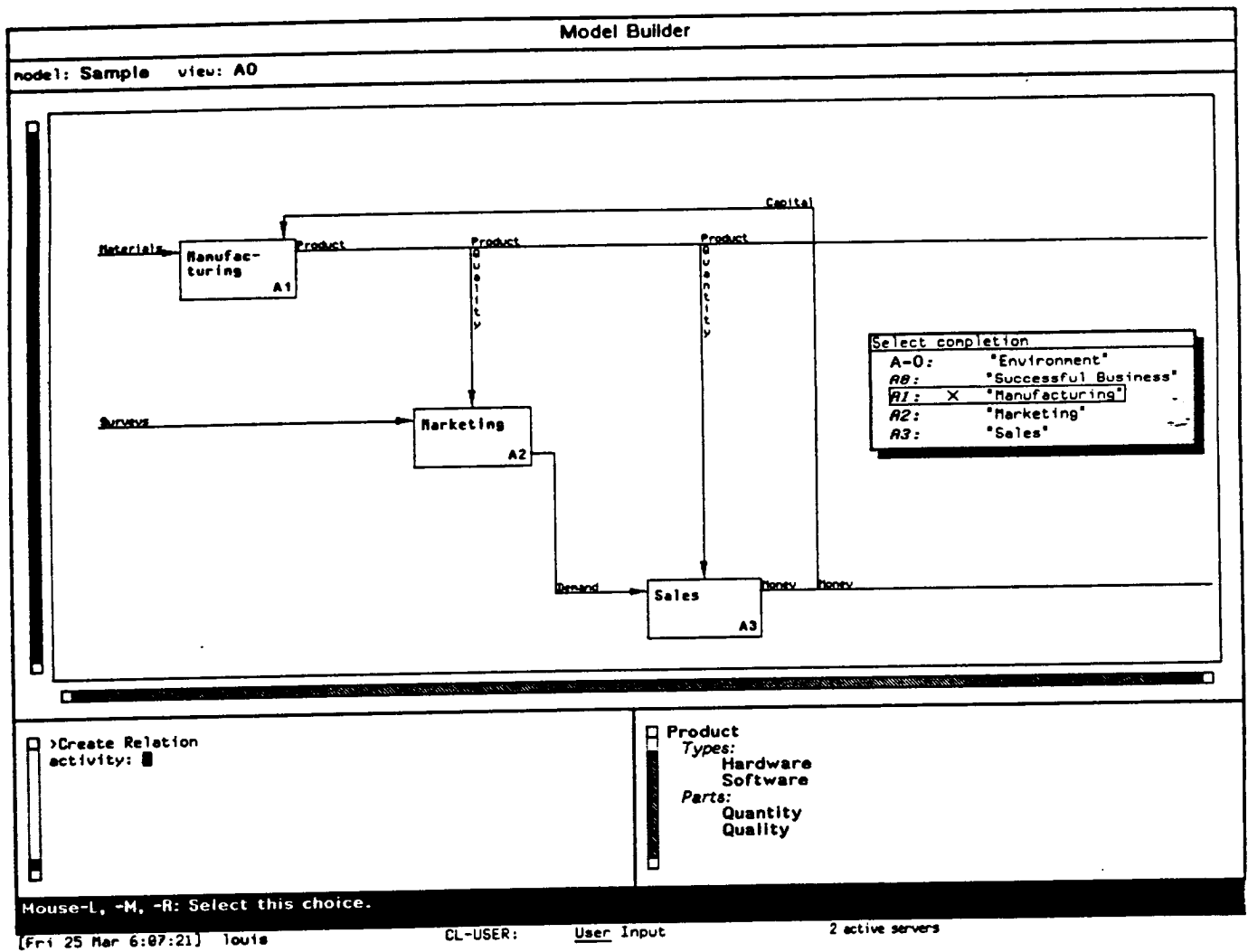


Figure 1.14: A sample of the IDEF0 modeling support screen.

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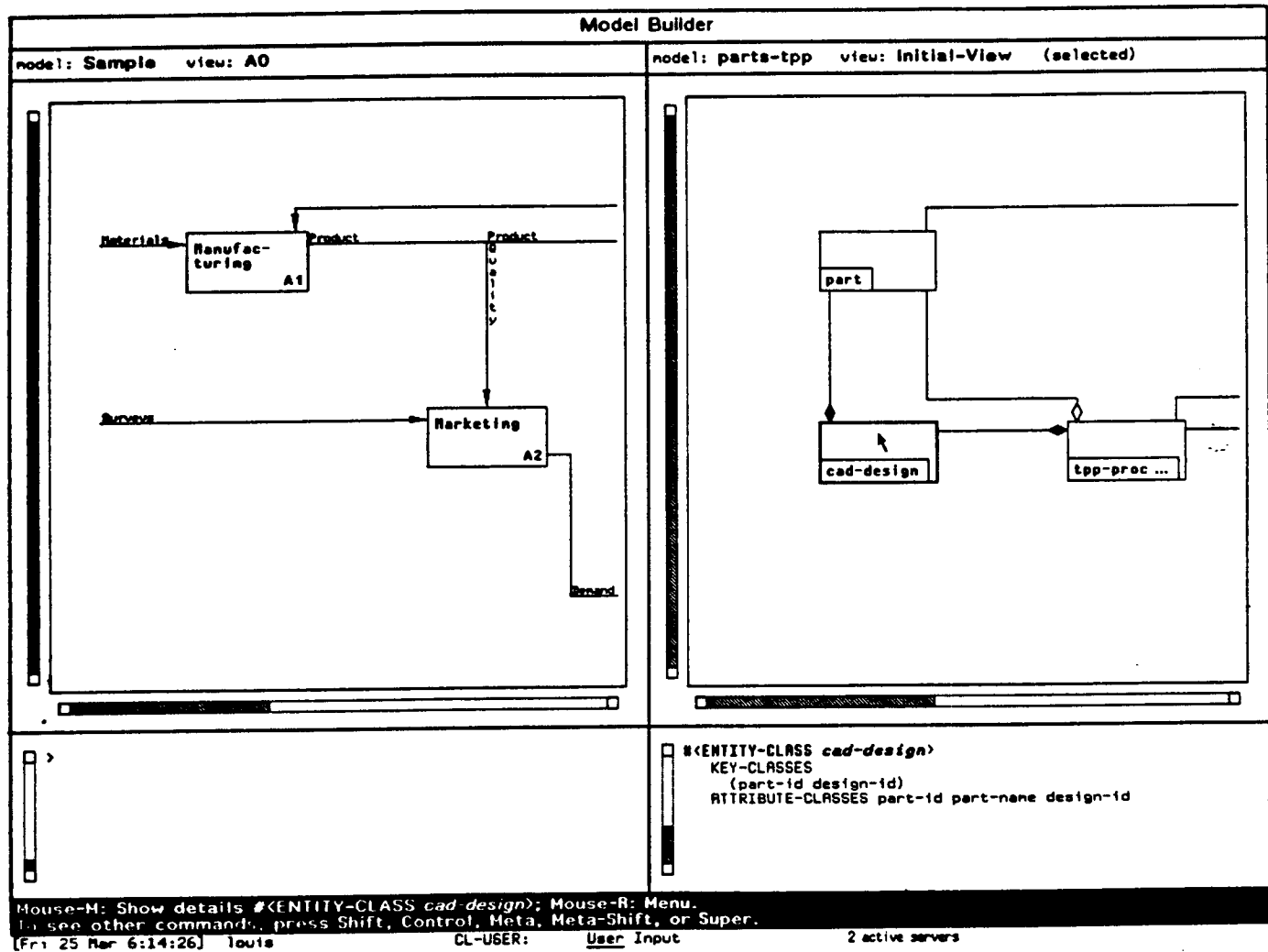


Figure 1.15: Multiple Modeling Support

Modeling Support for IDEF1

An IDEF1 model represents the structure of information needed to support the functions of a proposed system. The methodology provides a set of rules and procedures for creating an information model of a system. Also provided in the methodology is the necessary graphical requirements, text and forms to convey the information to the reader. The creation of an IDEF1 model is an iterative process that is organized into stages with measurable results and specific products. Like IDEF0, IDEF1 has a graphical syntax for representing the information in a model. In an IDEF1 model, a diagram consists of boxes representing the entity classes. The links between these boxes are the business rules that relate one information item to another. The cardinality of the relation of one piece of information to another may be one-to-(zero or one), one-to-(zero, one or many), or one-to-(one or many). Each of these relationship cardinalities has a special graphical representation. Figure 1.16 displays the basic components of an IDEF1 model.

Developing an IDEF1 model begins with gathering information about the system to be modeled. The next step in the process would be to extract data item references from the source data. The modeler would use these references to create a source data item list. The IDEF1 modeler will then extract from the Source Data List the initial guess at major information clusters. This establishes the candidate entity classes which will be put into the Entity Class Pool.

Using this Entity Class Pool, the modeler then established the definitions of the Entity Classes. As a constraint on the Entity Classes the links (Relation Classes) between the Entity Classes would be established. These Relation Classes must reflect the design rule and should allow no ambiguity of that rule. Once the Relation class has been established it would be added to the model.

Key Classes are included in the model next. The Source Data List would be used to identify the candidate data items that uniquely identify an entity class. This can be done by comparing the source data list and the items used to establish an entity class in the Entity Class Pool.

After these activities, the entity classes are populated by determining the key attribute classes and the non-key attribute classes. During this stage in the development of the model, new entity classes and relation classes will probably be added to the model. The addition of these new elements will also require additional attribute classes. As each of these elements are added to the model they are defined and added to the model dictionary. The completion of the process will result in a diagram that contains the structural characteristics of the information model. The diagram will follow a set of rules and procedures that provide a meaningful representation of the information modeled. As a part of the model, a dictionary will be developed that defines each of the model elements.

Prior to validation and acceptance, multiple modeler's models of the same information will likely be compared and merged to form one acceptable model. Involved in the validation and acceptance of a model will be reviews by the system design team and a model development supervisor in charge of the project. They must have

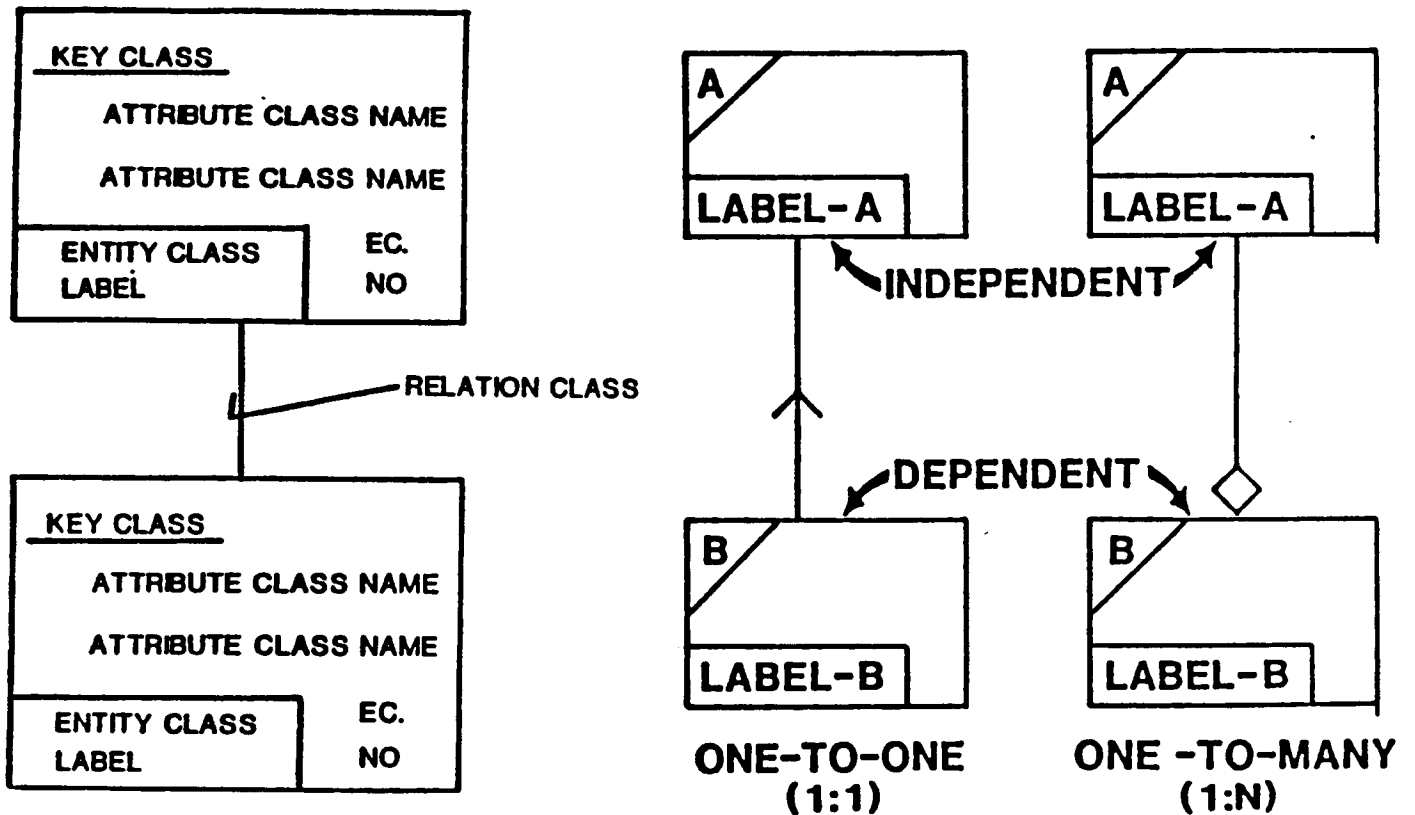


Figure 1.16: Semantics of basic IDEF1 syntax

the capability to comment on the model in various stages of its development and insure that the critical errors are fixed prior to completion of the model.

The process of merging entity classes may start with either the comparison of entity classes or the comparison of owned attribute classes. Choosing two model elements that are the same often includes the need to examine the textual description of the elements. The modeler may also go back to the original documentation associated with each to determine if they represent the same item. In merging two entity classes, the modeler can compare their owned attribute classes. If most or all of their owned attribute classes are the same, then the two entity classes most likely are the same. With the determination that two entity classes are the same, their relation to the surrounding entity classes must be resolved. Solutions must be found to any conflicts that may occur in the relation classes. The solution should preserve the system design rule.

Requirements for Auto-IDEF1

Much of the time in building models is spent in creating the diagrams by hand. The modeler develops the model and a draftsman then draws them by hand. Much time could be saved in the creation of the diagram with an auto-IDEF tool that allowed the modeler to create the diagram as he or she created the model. In large complex systems it is impossible for one individual to comprehend the total system. This means that in large system modeling many modelers will be involved in the creation of a model. Even though the same modeling technique is used, no two individuals will produce identical models. With multiple modelers working on a modeling project, one of the common activities that take place is the merging of models. Two models of the same system will be merged to form a complete model. Creation of a model will often be a process of modifying the model of a similar system. This would require the modeler to determine when an entity class really exists or not, if an attribute class should be removed from an entity class or not. When an entity class is removed, the attribute classes and relation classes that are associated with it must be removed not only from it but from the dependent entity classes as well. When owned attribute classes are removed from an entity class, the modeler must then remove all inheritances of that attribute class. The changing of relation classes would also have to be carefully monitored.

In order to satisfy the multiple needs for IDEF1 modeling support, a modeling tools is needed with the following features:

1. An accomplished IDEF modeler who is familiar with the IDEF tool should be able to create a valid IDEF diagram as quickly as drawing a rough sketch of the same information.
2. The degree of difficulty in learning to use the tool should be such that an accomplished IDEF modeler with minimum clerical and drafting skills could begin producing valid models with a few hours of training. A person with clerical skills and trained in the use of the IDEF tool should be able to enter,

update, and print an IDEF model with, at most, the same amount of effort as producing the text using a typewriter. One of the difficulties in learning to use a piece of software is the difficulty in learning the commands. Command completion and an easy to use help facility should enable a new user to begin producing valid models within a very short time.

3. The tools should provide consistency checking within the language definition. It should automatically insure that when in model creation mode that the modeler does not violate the rules and constraints of the language.
4. Model element definitions are an important part of an IDEF model and the Auto-IDEF tools should provide an editor like environment for the entering of these definitions. Those that review a model built using the Auto-IDEF modeler should be able to enter their comments about each model element. This facility should be handled in a manner similar to that for the model element definitions. The tools should provide for automatic creation of the required documents in response to a single command. In IDEF1, natural language description of the relation classes would be one of the documents provided. Other documents, other than the model itself, would be attribute class diagrams, entity class definitions, attribute class definitions, etc. Hardcopies of these documents should follow the prescribed IDEF1 format.
5. Automatic layout facilities should be provided. This should ensure that in the creation of a model there is a minimum number of line crossings. This facility will also allow for the reformatting of a model to ensure the minimum number of line crossings.
6. The tools should provide for the saving and restoring of a model. This ability of the tool should allow for the reusing as well as the editing of a previously entered model.
7. Model merging should be provided. Within the IDEF1 modeling tool this should include matching entity class pairs, merging of entity classes, copying model portions, and matching attribute pairs. To assist in the decisions that the modeler will have to make in model merging activities the tools should have a top level function to print statistics on any list of any type.
8. Minimum effort should be involved in the moving, deletion, and creation of a model element. The tool should automatically move all links when any entity class to which it is attached are moved. Deletion of any entity class should automatically remove the relation classes associated with it. All inherited attribute classes should be removed from the dependent entity classes automatically. The Auto-IDEF tool should always maintain the model in keeping with the IDEF1 language definition.

The design goals for the automated modeling support for IDEF1 can be summarized as follows:

1. Reduce cost and time required to build models by performing all of the drafting, consistency checking and by supporting the reusing of existing models.
2. Support traceability and validation
3. Provides support for composite modeling (system integration).

The modeling support for IDEF1 was also constructed using the Meta-modeler generation capabilities. The IDEF1 model of IDEF1 which was used as input to this generation feature is shown in Figure 1.17. Figures 1.18, 1.19, 1.20, and 1.21 display sample screens from the IDEF1 modeler.

The prototyped IDEF1 information modeling tool has the following features:

1. Allows modeler to focus on:
 - (a) Rules defining relationships within the CELSS design
 - (b) Design concept definition
 - (c) Logical relationships within the design team used for problem identification or requirements definition
2. Provides for concept model development support including:
 - (a) Entity class definition
 - (b) Link class definition
 - (c) Key class definition
 - (d) Attribute class definition
 - (e) Inherited attribute classes
 - (f) Attribute classes in key classes
 - (g) Inherited key classes
 - (h) Link class correspondence (strong-many-to-one, weak-many-to-one, one-to-one)
3. Allows creation, editing, commenting and management of the descriptions associated with the items listed above.
4. Supports auto-layout and routing of the completed network graphical representation of the IDEF1 model.
5. Supports validation of models including the generation of natural language text summaries of the models for review by domain experts.
6. Supports the integration of multiple information models, providing support for:
 - (a) Searching textual contents of entity classes
 - (b) Matching entity class pairs

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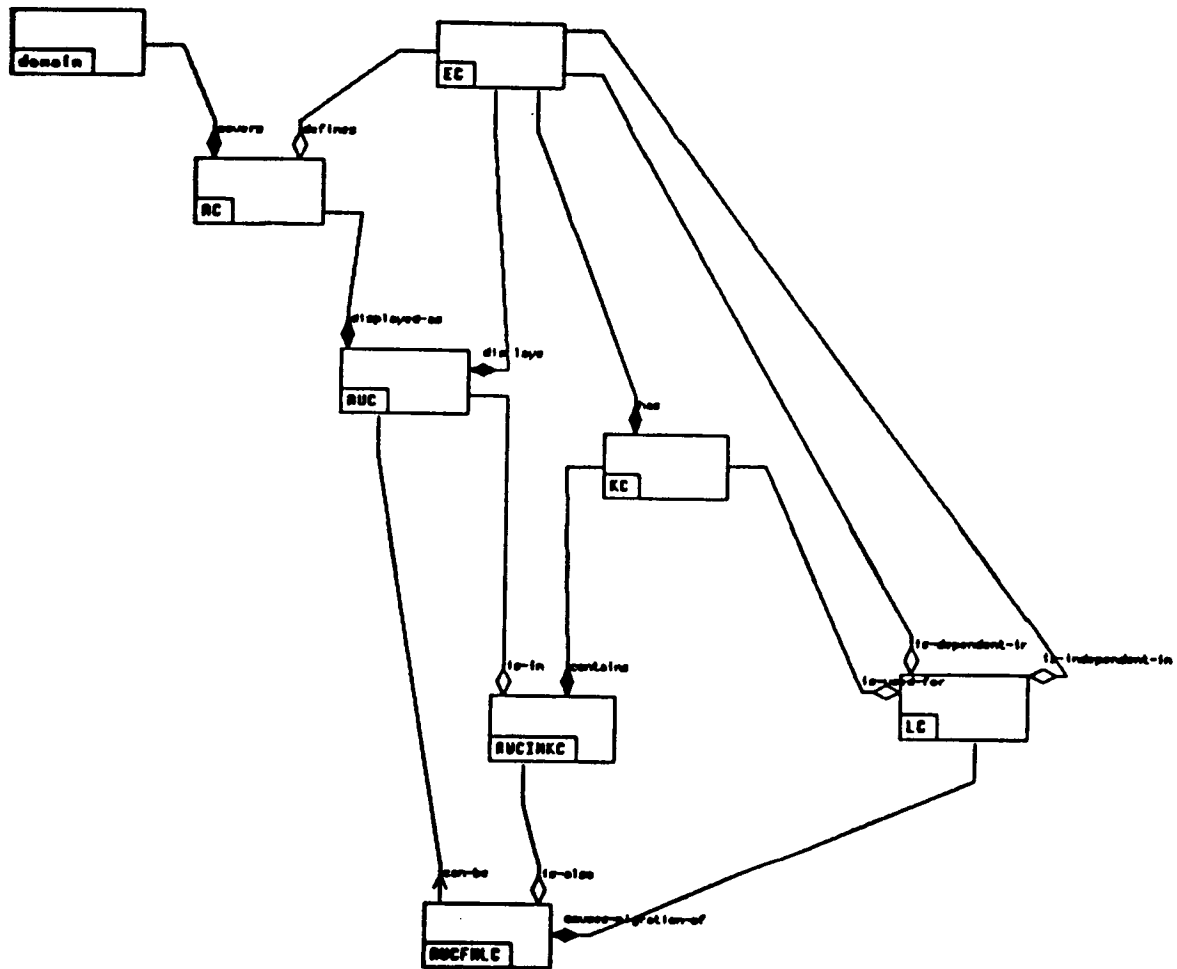


Figure 1.17: The IDEF1 representation of IDEF1.

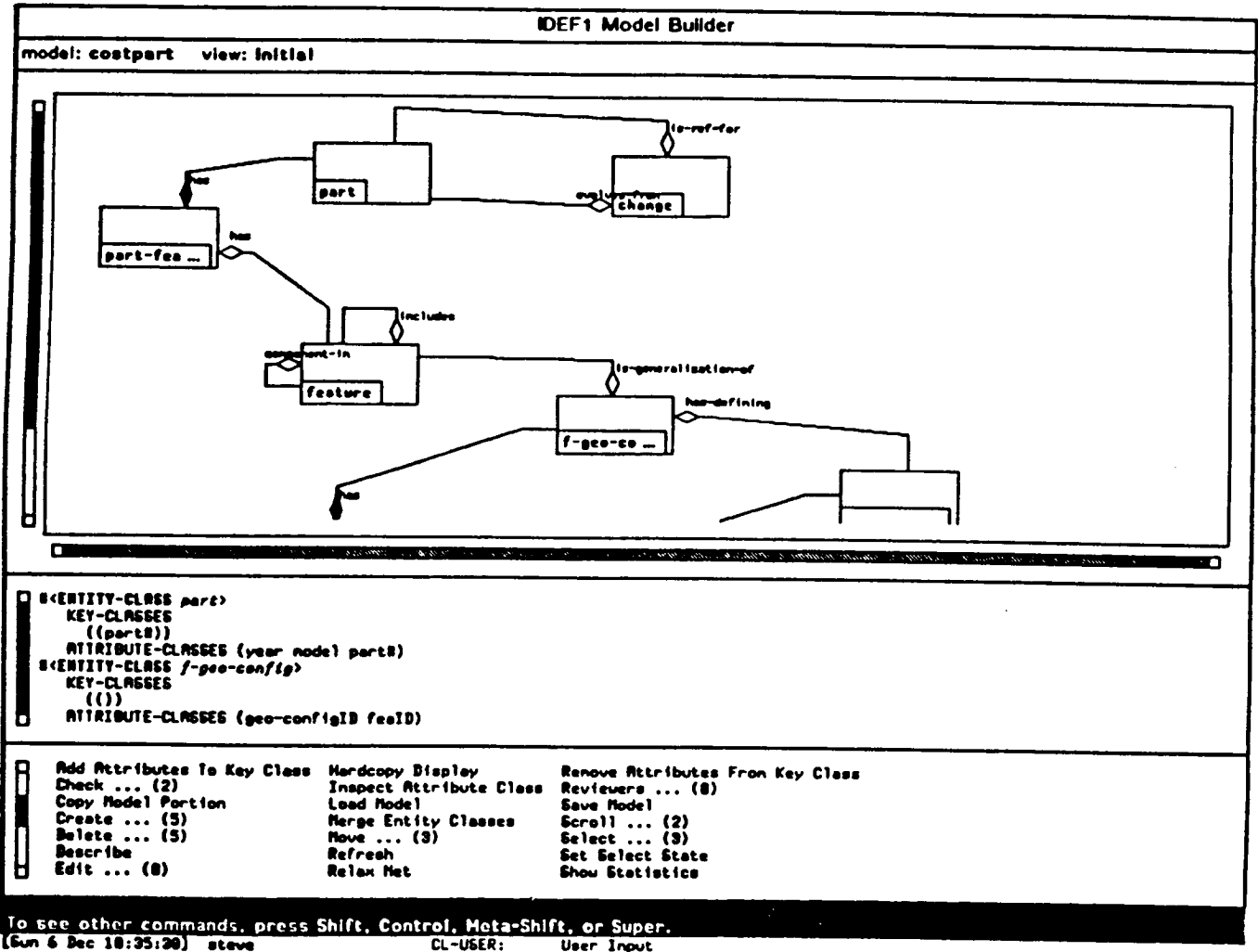


Figure 1.18: IDEF1 model building support interface

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	Project: objects	Rev:	Draft			
	Notes: 1 2 3 4 5 6 7 8 9 10		Recommended			
			Publication			

Entity Class Name: basic-link-class-mixin

Entity Class Label: basic-link-class-mixin

Entity Class Definition:

Entity Class Synonyms:

Key Classes: (model-element)
(from-entity-class,to-entity-class,unique-name,cardinality)

Owned Attribute Classes: from-entity-class
to-entity-class
unique-name
cardinality

Inherited Attribute Classes: [model-element, From: basic-model-element, Owner: basic-model-element]

Dependent Entity Class: link-class

Node:	Title: Entity Class Definition For: basic-link-class-mixin	Number: 8
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Figure 1.19: Sample IDEF1 Dictionary Data

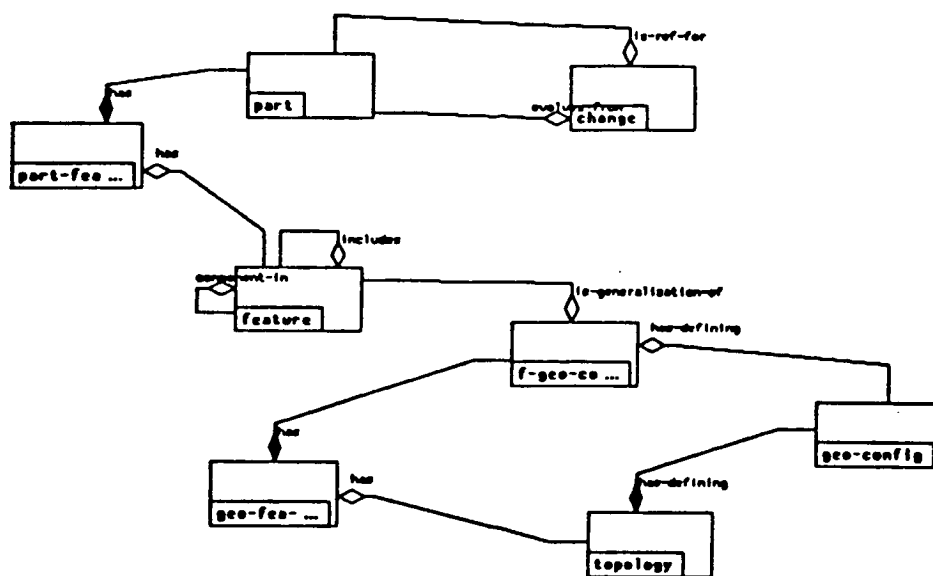


Figure 1.20: Printout of IDEF1 network representation

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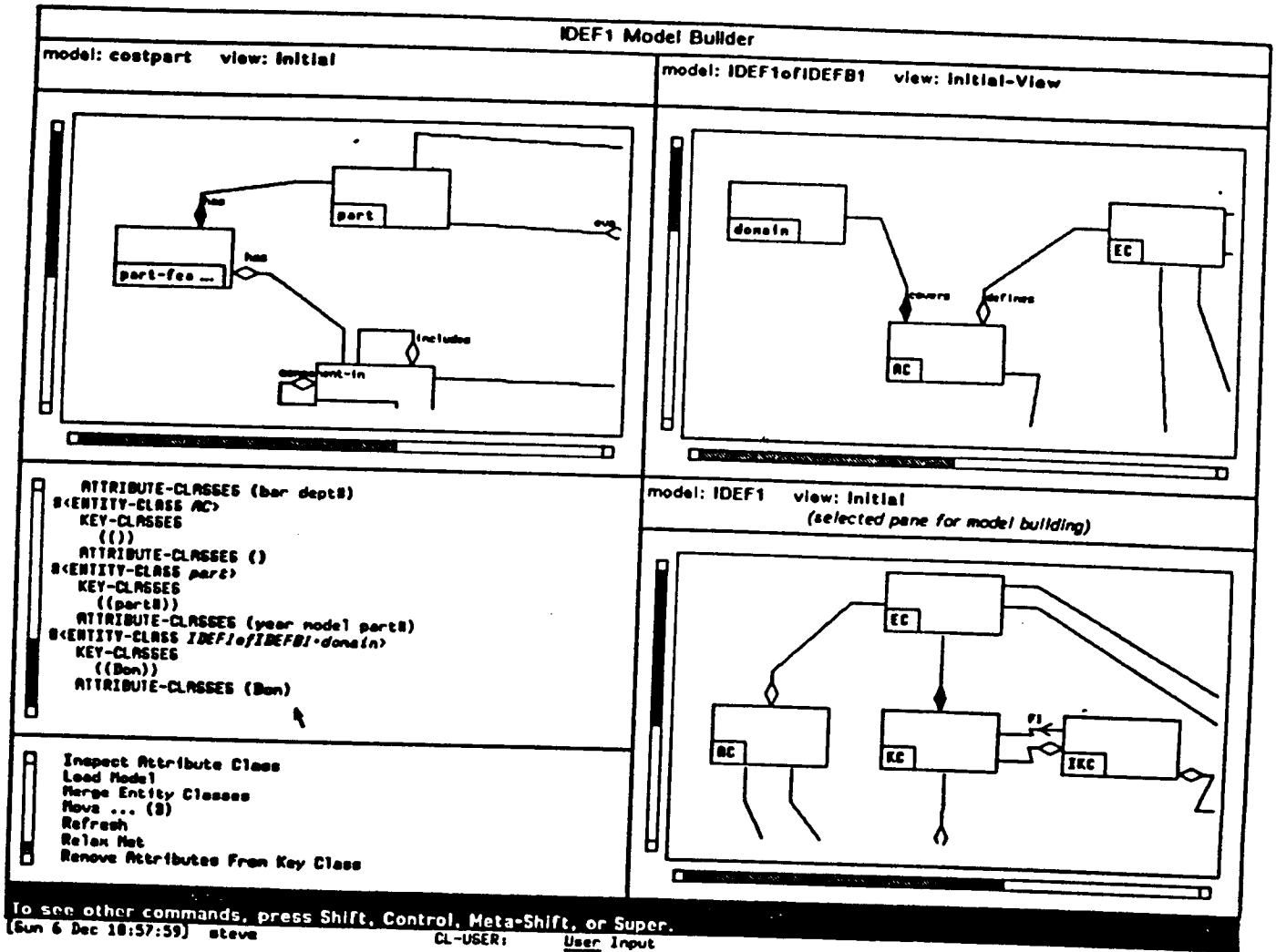


Figure 1.21: Multiple model integration support

- (c) Merging of entity classes
- (d) Copying model portions
- (e) Matching attribute pairs
- (f) Having a top level function print stats on any list of any type

Generalized Model Generator

The meta-modeler effort has been focused on development of an object based code generation system which would accept formal descriptions of a methodology and produce an intelligent modeling support tool from that description.

Almost all systems engineering requirements and design methods make use of a graphical syntax for display of the results of the application of that method. Simply providing a drafting tool for the production of these graphical language representations is often counterproductive for the analyst. What are needed are modeling tools which "understand" the graphical language and the underlying rules for correct expressions in these languages. Unfortunately, building such syntax directed modeling support tools is an expensive process. Also since the methods themselves evolve (even within a single project) it has been difficult to justify the expense of developing a model driven editor. The MetaModeler was designed to address this need. The current version of the MetaModeler generates a basic model data management tool to which the developer must add the user interface (see Figure 1.22). The concept of the metamodeler grew out of work in the formalization of systems development methods under the Air Force Integrated Information System Evolution Environment Project. This formalization work identified a base semantics for many of the systems development methods in wide use today. The metamodeler is a software implementation of the insights gained from this formalization work.

The graphical languages have many structural similarities. Typically, one class of model elements are displayed as two dimensional regions (often boxes). These boxes have links between them which display the relationships that exist between the elements represented by the boxes. Other components of the model would be descriptions and definitions. Operations common to most any modeling methodology would be creating, moving, scrolling, etc. Because of the similarities in the graphical syntax it should be possible to have a generalized model builder which also handles a large part of the graphical user interface generation as well as the model data management.

The MetaModeler provides a general way to create a computerized tool for any modeling methodology. It provides a specification language that allows the description of the syntax and grammar elements of modeling methodology. The first step in the use of the MetaModeling tool, is to describe the information structure and semantics of the methodology for which a modeler is to be designed. Using IDEF1 the programmer describes the entity classes and link classes in the specific MetaModeler language. The third step is to let the MetaModeler generate the model tool. The last step in the process is to add the user interface. Currently only the graphical display object management and link routing of this last step is automatic.

META MODELER CONCEPT

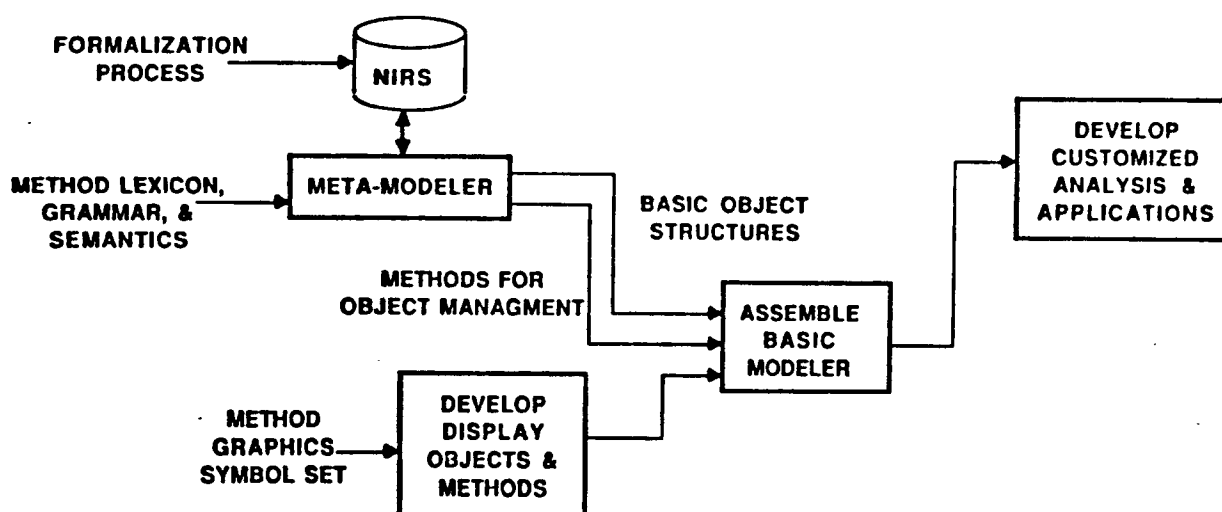


Figure 1.22: Use of MetaModeler to Generate Modeling Support Environments

The code generated by the MetaModeler consists of a set of Flavors object definitions and Lisp methods.¹ In the MetaModeler, the methods generated cover the basic model element management functions. These include creating, deleting, and editing a model element. Since both the lexicon and the grammar of a method is specified to the MetaModeler most of the consistency rules are automatically generated. For example, associated with deleting a particular model element may be actions such as deletion of all links between it and other elements in the model. Another function created by the MetaModeler is deleting a parent node. Deleting a node may involve automatically deletion of the logical children of that parent. The specifics of the graphical display, the various editing functions, and model commands (command structure) are not currently handled by the MetaModeler.

The current MetaModeler was used in the development of the IDEF1 and IDEF0 modeling tools. The value of the metamodel concept was proven in the development of these modeling tool in terms of development time savings and integratability of the resulting systems. The concepts behind the MetaModeler are still undergoing an evolutionary process and continue to change as more experience is gained with its use. Several weaknesses or features that are either desirable or need changing have been discovered.

The MetaModeler needs more generalization. Currently the MetaModeler is implemented as a macro which the programmer invokes on a file of method specifications. An improved user interface to the MetaModeler itself would make its use more attractive. In addition, the code generated at this time still requires the manual addition of error trapping and recovery code. Continued effort is needed in this area to make the code generated more resistant to failure. Some means to specify the graphical syntax of a methodology would be one step in improving the power of the MetaModeler. One suggestion is to add the ability to create nodes that could contain the node information and then be able to create relation types to other nodes that contain other types of information. This would provide a generic way to generate a tool that can describe systems. It would allow the user to do any graphical modeling methodology using the MetaModeler.

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¹These are the basic components of an object orientated system. In a Lisp machine, Flavors are the mechanism for defining, creating, maintaining and using objects. These objects are capable of acting on messages that they receive. Flavors have associated methods which define the actions associated with messages. These methods are the functions that act on a particular message that an instance of a flavor receives.

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SECTION II

MODELING

Chapter 2

A TIME-STEP SIMULATION MODEL FOR A LIFE SUPPORT SYSTEM

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Chapter 2

A TIME-STEP SIMULATION MODEL FOR A LIFE SUPPORT SYSTEM

In building any complex computer model, one first tries to define as many common features among the different component parts as possible and model these parts in a generic manner. Thus, in procedural computer languages such as Fortran, subroutines which do common procedures are defined once and called repeatedly with different input parameters. This same desire for efficiency in object-oriented programming languages led to the development of data structures, flavors, and similar constructs for representing objects. In LISP the flavor system can be used to define generic objects which in turn can be incorporated into the definition of other objects for ever increasing detail.

A human life support system for a small enclosed space can be thought of as a collection of boxes each of which has a specific task or set of tasks to perform upon the materials inside it. An object-oriented computer model of such a life support system can be composed of a collection of objects each corresponding to a box in the real life support system. The kinds of information attached to the computer objects depend to a great extent on the use to which the computer model will be put. For instance, a time-step simulation model requires that each object has information about what kinds of stuff it contains, what to do to it and where to put it when it's through. As a front end to a dynamic simulation model, which solves simultaneous differential equations, the object-oriented model requires that each object have a differential equation representation of its behavior, its initial conditions and stream equivalences between objects.

The object-oriented computer model described here was built as a time step simulation model due to time limitations. It is recognized that a dynamic simulation model would more closely model the behavior of a real system and would be more useful to engineers for the design of individual components, subsystems and control subsystems than a time step model. Future work in this area will involve combining the natural orientation of object-oriented programming and the power of dynamic modeling to create an engineering tool for designing and simulating complex life support systems.

COMPUTER STRUCTURE OF GENERIC LIFE SUPPORT SYSTEM

Computer Environment

We chose to build our model of a closed loop life support system using Knowledge Engineering Environment 3.0 (KEE) by Intellicorp, which is an objected-oriented knowledge base shell. We used a Symbolics 3640 computer which has a LISP architecture and runs the Genera 7.1 operating system with Symbolics Common LISP.

Basic Structure:

Our first goal was to build a generic life support system model which contained at least one object to do each of the tasks necessary in a real life support system. Thus objects representing crew members, carbon dioxide removers, water condensers, trash incinerators, crew cabins, oxygen stores, etc., were needed. For programming efficiency, we categorized these objects into a few basic generic component objects which represent the major kinds of boxes in the real life support system. The kinds of objects we needed were reactors (which include biological reactors such as human beings and plants), stores for storing food, gases and liquids, and the pipes which connected reactors and stores together.

Detailed Structure and Auxillary Routines

We then used these generic objects to define more specific reactors and stores, providing specific information for each which served to define and distinguish them. LISP functions were written to describe the behavior (mainly chemical) of each reactor for the time-step simulation runs and to provide a rudimentary control system. Many specialized functions, parameter definitions, configuration and consistency checking routines, simulation drivers, object modification windows and data handling routines have also been written in LISP and using KEE constructs such as Active.images and Active.values. Most of these LISP functions were designed to help the user in building a specific life support system configuration. For example, one set of functions provide automatic definition of pipes between reactors and stores with mouse-sensitive pop-up menus of possible choices and the opportunity to specify missing information needed to make or hook up the pipe. Since a typical configuration contains over one hundred pipes, this feature alone has saved a great deal of repetitive work.

Life Support System Configurations

The idea was to use this generic model, build specific configurations and compare how they perform by running multiple simulations. Three configurations have been built. The first contains an algal culture vessel for growing food and exchanging carbon dioxide for oxygen. The second contains a biomass culture vessel for growing wheat which serves the same basic functions as the algae culture. The third configuration contains no plants. All food is supplied from outside the system and the conversion of

CO₂ to O₂ is accomplished by a Bosch reactor coupled with a water electrolysis unit. All configurations contain these last two reactors but rely on them in different degrees. These three specific LSS configuration models are called LSS-1, LSS-2 and LSS-3, respectively.

Component Sharing

In true object-oriented style, most of the specific components in each of the configurations are shared. Thus, all the components of the RITE waste disposal subsystem, the crew members, the major food, liquid and gas stores, the crew cabin and air purification/regeneration subsystem are common. In fact, a configuration is specified by a simple list of all reactors which is combined in a special way with a list of all reactors not included. The simulation driver runs by sending a message to each reactor in the configuration list in turn to perform its input/output and reactions. Those reactors not in the configuration list are not sent messages so do not participate in the action. This is a very efficient way of building speculative models like the LSS models since a single component can be used in any number of configurations. Changes made to a single component need be made only once and all configurations are always current. If a change is to be made to a component for only one or a few configurations, then a new instance of the generic object can be made with the desired changes, and the configuration list modified to incorporate the new component.

IMPLEMENTATION OF THE GENERIC MODEL

System Complexity

We found we could not coerce a realistic definition of a reactor into a simple set of reactions and connecting pipes. Reactors became more complex with internal compartments so the distinction between components and subsystems is blurred. The contents of the reactors, the chemical species, are moved around by the reaction subroutines between compartments and changed forms in reactions limited by the abundance of specific chemicals or other parameters. The need to control the flow of chemical species between reactors and stores in realistic and dynamic ways necessitated putting more flow rates under control of the reactors. Thus, what was supposed to be automatic within the generic life support system sometimes became specific to each component. Since the reaction subroutines for each component or component class must be written separately, a lot of component specific code has been written.

Compound Database

It quickly became obvious that the amount of information needed on each of the chemical species floating around within system components was too much to be coded into the reactor's reaction subroutine. Since some of the information is needed by several subroutines, it was decided to build a compounds database to hold all this varied information. Although still in its infancy, the compounds database contains

information on molecular weight, phase (gas, liquid or solid), metabolic products with weights, chemical formula, combustion products with weights, catalytic products with weights and absorption rate for digestion. Thus, the same compound can be eaten or combusted with or without the same results and NO_2 can pass unchanged through an incinerator only to be catalytically reacted to N_2 and O_2 in the pyrolyzer. Compounds such as N_2 which are not changed by a reaction such as combustion are their own reaction products and therefore do not have to be handled differently from compounds that do react.

Generic Compounds

One very nice thing about the idea of the compounds database is that the concept of a compound is very general. Anything, not just a compound in the true chemical sense, can be specified as such if a formula and breakdown products can be designated. Mixtures of compounds are good examples. Meals (breakfast, lunch, supper and snacks (Moon Pies and Mars Bars, only)) are specified as part of the Foods branch of the compounds database and are composed of varying proportions of protein, fats, carbohydrates, fiber, and water. The molecular weight of breakfast, for instance, is the total gram weight of its component foods. Subroutines have been written to calculate the combustion and metabolic products and proportions from the component foods list of the meal.

Higher Plants Growth Parameters

Higher crop plants, so far only wheat, have ten or more special slots for specifying growing characteristics. Thus a higher plant biomass reactor need only carry information specific to the reactor, such as light intensity and the mixture of gases in the plant growth chamber. Plant specific information such as growth rate, edible proportion, water transpiration rate, respiration rate, seed weight and growth period, is in the plant subclass of the components database. Some of these parameters vary with the age of the plant so are specified as vectors, the length of which equals the growth period. The actual amount of plant material, on the other hand, is a characteristic of the biomass reactor and is carried in two slots: the plant.age.vector and the age.mass.vector. So far the only growth limitations in the biomass reactor is the light intensity and the amount of CO_2 . Random and condition specific mortality of plants throughout the growth period, but especially for young plants will be incorporated in the next phase of development.

Control Subsystem

The control subsystem for the GENERIC LIFE SUPPORT SYSTEM, which was envisioned at first, was thought to be too complex to be implemented in the time allotted. Some form of dynamic control system was necessary, however, since changing conditions during a simulation run made constant rates impractical. Temporary patches to these problems were made by putting conditional statements in the reactions which allowed some of the reaction or input/output rates to vary according to the values of critical parameters. Other patches took the form of individually specified equations for the amount of material to be

moved through a pipe. With so many pipes in a configuration, it was hoped that this amount of individual programming could be avoided. A formal control subsystem and generic pipe input/output methods will be implemented in future versions of the generic life support system.

Component Compromises

Compromises had to be made in the classes of components originally planned.. For instance, we had hoped to link reactors only to stores and vice versa, but this soon proved to be too limiting so we created a hybrid object called a *store.reactor*. In the best style of object-oriented programming, these *store.reactors* contained all the features of both reactors and stores. Since all three configurations have more *store.reactors* than pure reactors, future versions of this model will not distinguish the two types of reactors.

DESCRIPTION OF THE GENERIC LSS MODEL AND ITS SYSTEM COMPONENTS

The generic life support system model was designed to facilitate building specific components and fitting them together into a complete system. It was desirable to have the specifications of each component contained in one of only a few types of object structures. This information is then available to generic LISP subroutines during the course of a simulation run. This was done in order to minimize the amount of unique LISP code needed for each system component. In the following discussion, KEE units are in small capital letters and slots which carry information about the attached unit are in italics.

Major Types of Component

REACTORS: REACTORS is the largest class of system components and contains most of the complexity in the model. Crew members, plant and algae biomass reactors, chemical reactors, pumps, and separators are all REACTORS. REACTORS control the rates of both the input and output of materials via PIPES. The PIPES that are attached to a particular REACTOR are listed in its *reactor.pipes* slot. The flow rate of material going through a PIPE is determined by the difference in the actual amount of the material in the reactor and a desired amount, but is never greater than the maximum flow rate of the PIPE. The desired amount may be constant or a function of the reaction rate. Output PIPES have negative flow rates.

In general a REACTOR is linked to STORES at both the incoming and outgoing ends of its PIPES. In a few cases a REACTOR is linked to another REACTOR. This is called "tight coupling" and requires a special construction. A REACTOR which receives material directly from another REACTOR is created as an instance of both a REACTOR and a STORES class, inheriting the characteristics (slots) of both. The materials listed in the *contents.vector* slot of the REACTOR/STORE is identical to the *state.vector* slot (or a

subgroup thereof). This is insured by an active value attached to the *contents.vector* slot. The REACTOR/STORE does not in this instance control the input of these materials (they are controlled by the outputting REACTOR) and the transporting PIPE is not listed in the *reactor.pipes* slot.

The *reaction!* slot holds the reaction equations while the *state.vector* and *parameters* slots hold other information related to the operations of a given reactor. The *state.vector* slot holds species names, masses and compartments for chemicals on both sides of the mass balance equation. The *parameters* slot holds the values of rate constants and reaction rates. The slot *reaction!* contains a LISP subroutine representing the time dependent reaction equation for the REACTOR. This subroutine alters the masses in the *state.vector* as a function of the time increment and the constants and reaction rates in the *parameters* slot.

Some REACTORS, such as PUMPS, chemical SEPARATORS and CREW members, have reactions that do not change one species of chemical into another, but rather transfer a species from one compartment to another. This is accomplished by specifying the compartment for each species in the *state.vector* slot. The formation of urine is one such reaction which takes water out of the blood and puts it into the bladder. Compartmentalization is an important concept since urination depends on the amount of water in the bladder whereas thirst and drinking depend on the amount of water in the blood.

STORES: STORES are passive units which do not directly control their own input and output. Most STORES are intermediate between two REACTORS. When material from one STORE is needed in another STORE, a pump is installed in the PIPE between the STORES, effectively dividing it into two PIPES which act independently. Since a PUMP is a REACTOR, its *reaction!* subroutine simply moves the material which is in the input compartment to the output compartment (see the last paragraph under REACTORS above). During the input-output phase of a simulation run (see Simulation Flow below) all of the output compartment's contents are emptied and the input compartment is refilled. Thus, it takes two timesteps to move a given quantity of material from one STORE to another through a pump.

PIPES: A PIPE moves materials between a compartment in a REACTOR (in the *reactor.end* and *reactor.compartment* slots) and a STORE (in the *storage.end* slot). The LISP subroutine in the *input.output!* slot determines the amount of material(s) to be transported as a function of the difference between the desired levels of total mass in a compartment (in the *desired.amount* slot) and the actual levels in the *state.vector* of the controlling REACTOR.

Input PIPES (into the REACTOR) have positive rates and output PIPES have negative rates. The absolute value of the transport rate can not exceed the value in the PIPE'S *maximum.rate* slot, nor the capacity of the STORE.

SYSTEM.

FUNCTIONS: The SYSTEM.FUNCTIONS unit contains a variety of slots and LISP subroutines. Some check for completeness in any given LSS configuration (*Check.configuration!*, *System.components*, and *System.pipes*). Others obtain user specifications for and execute simulation runs (*Reset.for.rerun!* and *Simulation.driver!*). Still others store output data for future analysis.

LINKAGES BETWEEN COMPONENTS

The components of an LSS configuration are linked together in two ways: physically linked by PIPES carrying materials and logically linked by the flow of information and/or control. Figure 3 show the major STORES and REACTORS and the PIPES connecting them.

A PIPE can represent a real physical entity such as a water PIPE between the WATER.STORE and the ALGAE.REACTOR. Or it can represent a somewhat less definite entity such as the PIPE carrying air between the crew CABIN and a CREW member's lungs. Regardless of the physical counterpart, all PIPES are members of the generalized PIPES class and basically work in the same way during a simulation run. During a given time step, the amount of material transported is determined as discussed above. This amount is then adjusted by the maximum flow rate in the *maximum.rate* slot of the PIPE if necessary. Finally the flow rate is checked against the amount in the supplying or receiving STORE, and again adjusted if it violates the storage limits. The amount is then added to the appropriate mass(es) in the *state.vector* of the REACTOR in the *reactor.end* and subtracted from the *contents.vector* slot of the STORE in the *storage.end*. Output amounts are negative so that the *state.vectors* and *contents.vector* are decremented and incremented, respectively.

The flow of information between system components is more varied than the flow of materials and does not have a single physical counterpart by which the transfer takes place. Information flow is accomplished in the CELSS model by "passing messages" between system components. A message can be either a request for information, such as a mass value, or a command to the message receiver to do a specific task, such as increase reaction rate. Information flow is an integral part of the dynamic control aspect of the CELSS system.

SIMULATION FLOW

A simulation run of an LSS model consists of several phases: 1) user specification of certain initial conditions, 2) simulating the changes in the *state.vectors* and *contents.vector* slots of REACTORS and STORES, respectively, over time, and 3) reporting of results of these changes back to the user. The initial conditions for REACTORS and STORES are stored in the *initial.state* and *initial.contents* slots, respectively. Only one configuration is specified for each simulation run. A mouse-menu routine using special features of KEE for building user interfaces will be employed so that reinitialization can be accomplished relatively easily.

A simulation run consists of looping through a series of time steps, updating the *state.vectors* of REACTORS and *contents.vectors* slots of STORES during each step. The amount of the time per step is fixed and is used to calculate the amount of change of the masses of materials in each STORE and REACTOR. Change is accomplished both by transfer of materials between system components and change of species masses within REACTORS. During a single timestep, two passes are made throughout the entire system. First, all of the inputs and outputs are done via PIPES. Then during the second pass, all of the internal reactions of the REACTORS are done. Since all PIPE transfers are independent of one another and likewise all internal reactions are independent, the order of execution of transfers and reactions within each group is not critical.

The results of a simulation run, mainly consisting of the levels of materials in the major stores, is dynamically reported using active images, a major feature of the KEE user interface building facilities. This is especially useful during the initial phases of building an LSS model while adjusting the sizes of the components to obtain a balanced model. While doing the simulation runs for system configuration comparisons, output parameters will be stored in files for later analysis and printed graphic display.

THE STRUCTURE OF THE CELSS - THREE CONFIGURATIONS

The structures of the three configurations are shown in Figures 2.1, 2.2 and 2.3. It should be noted that the only difference in the figures is in the upper right hand corner where the algae or higher plant subsystems reside. The main reactor in both plant subsystems are the biomass reactors although several other reactors and small stores were necessary to handle the special input and output needs of the main reactors. The two biomass subsystems also share some components between them: the ammonia synthesizer and storage tank and the nutrient salt store (containing the generic compound nutrient.salts). The rates and percentages referred to in the next several paragraphs are either user supplied or the results of simulation runs based on user supplied numbers. Some of these numbers represent real rates such as the O₂ and CO₂ constraints in the algae biomass reactor. Others are mere ball park guesses awaiting experimental evidence.

Closed Loop Life Support System: Schematic Representation of Units within the LSS-1 Computer Model

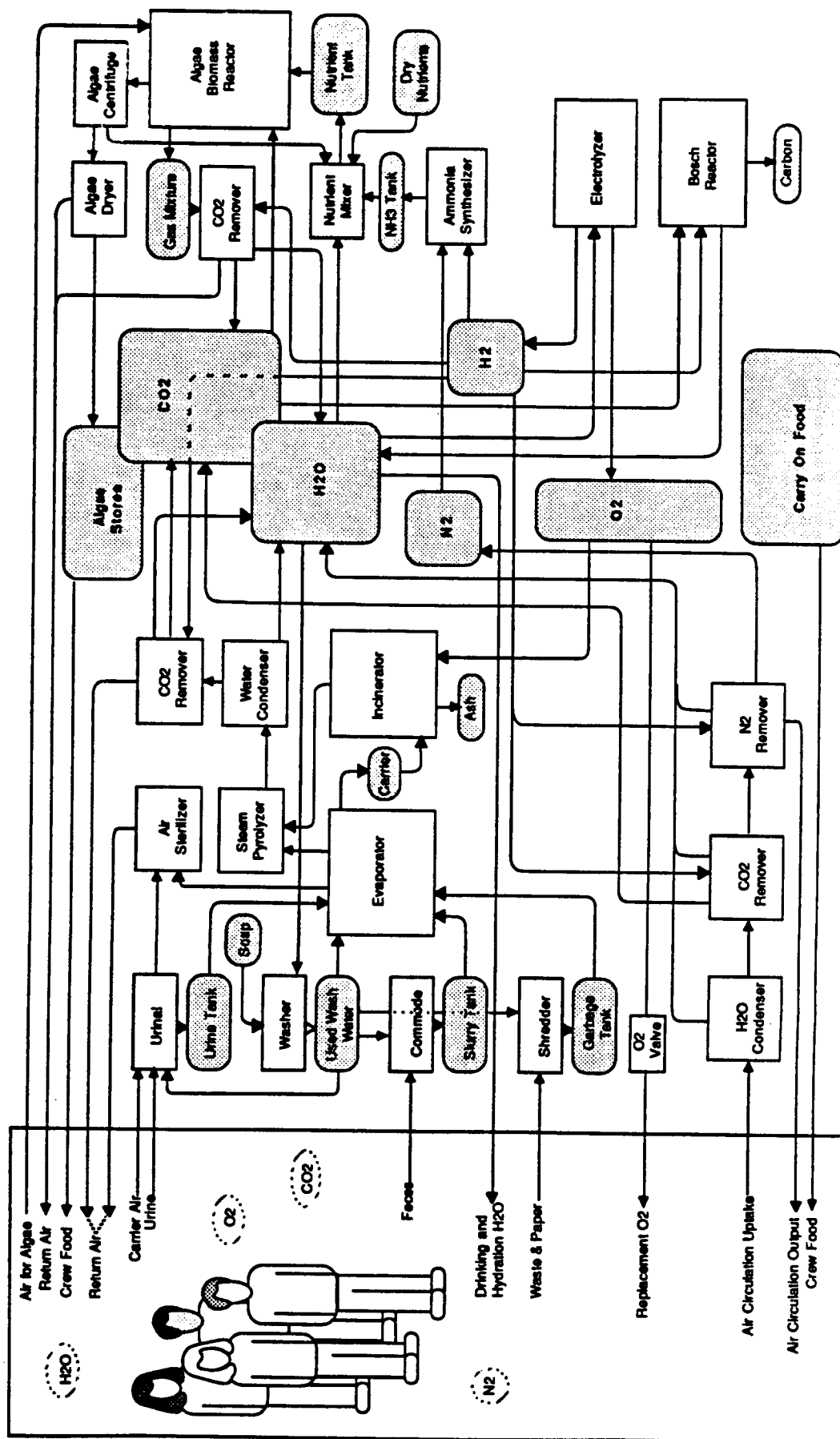
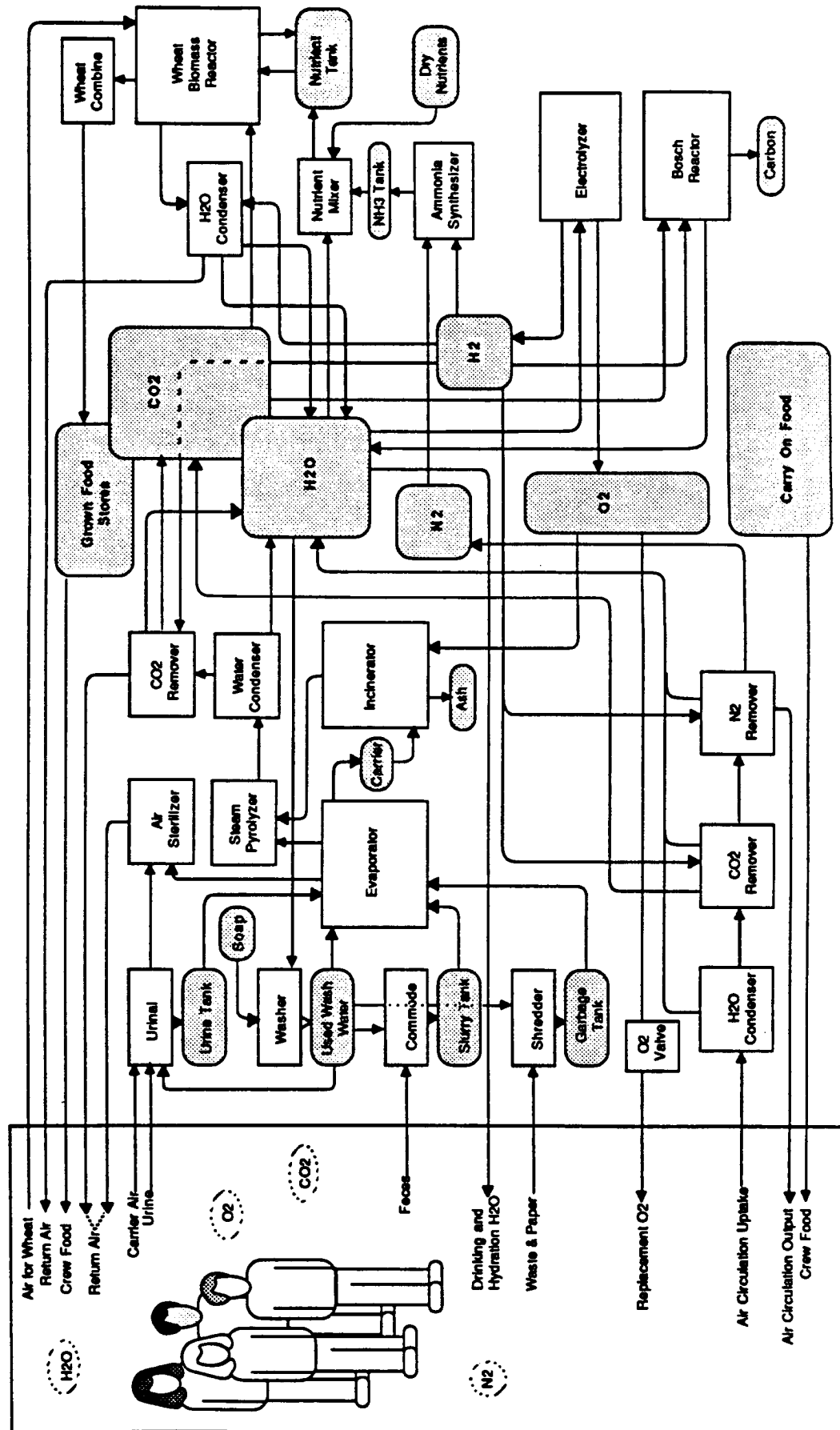


Figure 2.1

Closed Loop Life Support System: Schematic Representation of Units within the LSS-2 Computer Model



**Closed Loop Life Support System:
Schematic Representation of Units within the LSS-3 Computer Model**

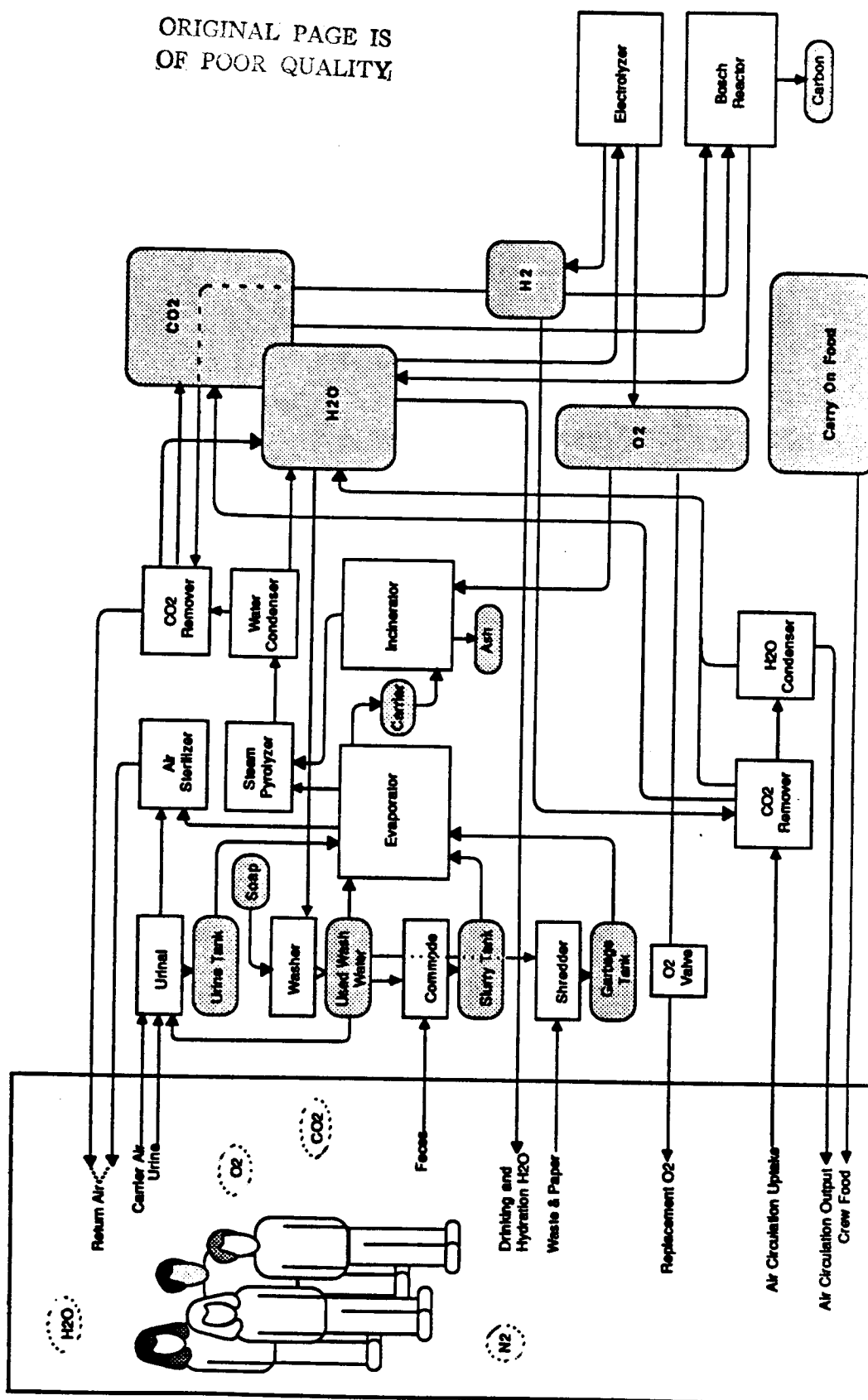


Figure 2.3

It must be stressed that the performance characteristics of these components have not yet been tuned. The result is that the preliminary simulation results which are presented in this report must be considered as indicative of a functioning life support model incorporating basic regenerative components, and not as an optimized system. Results are presented only to show what type of outputs are generated by the program. The following discussion refers to these preliminary results.

LSS-1: ALGAE BIOMASS REACTOR CONFIGURATION

Growth Phase

The algae biomass reactor is envisioned as a tank containing gases, water, inorganic salts and algae cells. In microgravity these substances would not layer out as they do on earth but most probably exist as a bubbly slurry which is gently moved past a light source. As the algae grow the slurry becomes thicker and it is necessary to add water (with nutrients). Water is added in 500 ml amounts whenever the cell density exceeds 1%. This continues until the total volume of water and cells reaches 100 liters.

Harvest Phase

When the algae reactor has reached its maximum capacity of 100 liters and the algae exceeds a 1% solution, the harvest procedure is initiated. At harvest 25 liters of water with 250 grams of cells are taken out and put into a centrifuge which concentrates the cells. After the cells contain only 50% of their weight in water, the supernatant is drained off back into the nutrient tank and the damp cells are placed in an algae dryer where the water is reduced to 5% by evaporation. The reclaimed water from the centrifuge is mixed with new nutrients and ammonia, ready to be added to the algae reactor as needed to dilute the growing cells. The specified growth rate of the algae is such that a given number of cells would double in 24 hours. The actual growth rate is limited by light intensity and by CO₂ availability. With these specifications and the CO₂ equilibrium concentration reached in the crew cabin, harvest occurred about twice a day. Thus the growth rate of algae in this reactor is about 500 grams per day.

Gas Concentrations

The concentrations of CO₂ and O₂ within an algae reactor are critical. Carbon dioxide concentration can be as high as 5% of gases. Oxygen, however, must be kept within one to two percent of 20%. This oxygen constraint means that the gas portion of the algae reactor be either very large or have a relatively fast through-put. The gas through-put rate is about 12 liters per minute and the capacity is 230 liters. Gas can be drawn out of the algae culture in microgravity with a cyclone device which produces an artificial gravity due to centrifugal force. Gas is cycled between the crew cabin and the algae reactor. The return stream has any remaining CO₂ removed chemically. After near steady state in the crew cabin is

reached, the algae has sufficient CO_2 without supplemental inputs from the CO_2 tank. The mean O_2 concentration in the algae reactor is nearly 23% which in reality is a bit too high. The main problem seems to be that the incoming air has already 22.4% oxygen which is also a bit high. It is obvious that other subsystems need to be investigated and adjusted in order to fine tune the gas balance in the algae reactor.

Diurnal Rhythms of Algae

The lights are kept on 24 hours a day in the algae reactor in order not to allow the algae to synchronize. This greatly simplifies the growth functions for algae since only the net gas exchange need be considered and the growth rate can be considered as a constant. This constancy in the algae culture is not only handy computationally but is absolutely necessary in a controlled system. In nature algae are synchronized by the day/night cycle and subsequently all divide nearly at the same time. If a similar situation existed in the algae culture the gas exchange properties would vary dramatically during the course of a cycle and other parameters such as cell and nutrient concentrations would be very difficult to control. By keeping the cells asynchronous, cell division and growth occur randomly so that on a total population basis growth and gas exchange appear constant. It is very critical to keep cyclical events from entraining the cells: thus, harvest which occurs twice a day in the model, must in reality be very gentle on the remaining 750 grams of cells lest they start cycling enmass. These and other considerations concerning the culture requirements for algae are presented in section III, chapter 3.

Nominal Simulation Run for the Algae Model

Figures 2.4a through 2.4c show the overall, cabin and store levels, respectively, for the four major gases and water during a two week simulation run for the LSS-1 configuration. The starting conditions were deliberately different from the near steady state in order to test the robustness of the model during the transition phase. The model has not been calibrated for optimal conditions - for instance, the through-put rates of the cabin CO_2 and water remover are relatively low so that the steady state CO_2 concentration in the crew cabin is 0.89% or nearly 30 times earth atmosphere. This may be good for the algae culture but not so good for the crew and probably 10 times the optimal for higher plants. The steady state water vapor concentration in the cabin is 1.22 %. The demand for O_2 is heavy during the first 24 hours because of a relatively heavy load on the waste system's evaporator and incinerator. After the initial period waste is put into the RITE system as it is made. The O_2 , H_2 and CO_2 stores are kept within reasonable limits by varying the rates of the electrolyzer and the Bosch reactor.

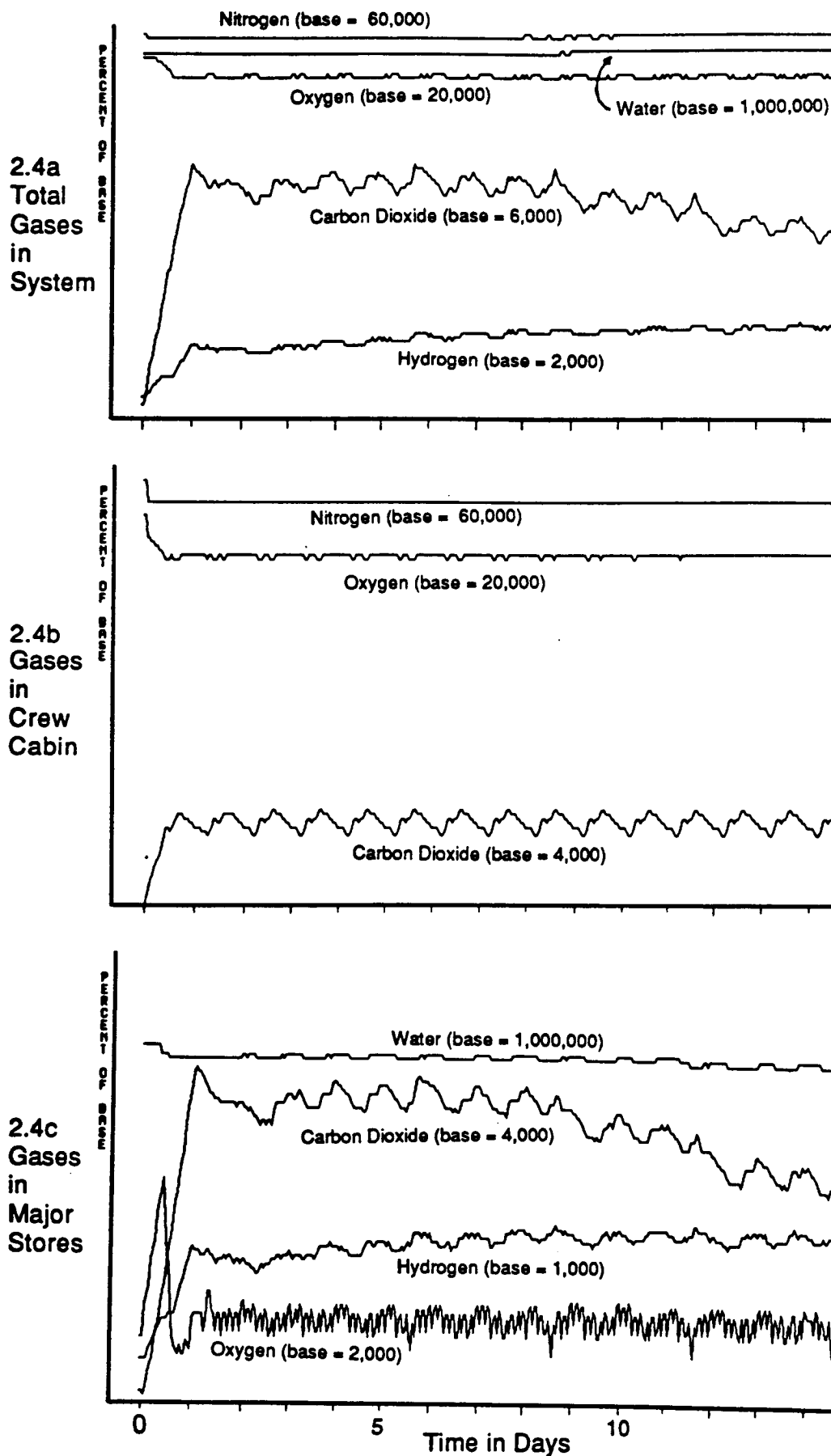


Figure 2.4a - 2.4c Relative abundance of gases in LSS-1 (with Algae Bioreactor) over 14 days.

LSS-2: HIGHER PLANT BIOMASS REACTOR CONFIGURATION

Wheat Biomass Reactor

Growing wheat is more complex to model than growing algae. The wheat reactor allows the simultaneous cultivation of wheat plants of all ages from 1 to 55 days. A light-dark cycle is allowed (though not required) which greatly affects gas exchange and transpiration (the uptake of water through the roots and output of water vapor through the leaves into the chamber atmosphere). Growth and thus gas exchange are calculated each time-step and are limited by light intensity and CO₂ concentration. As described above in the section on the higher crop plant database, the growth characteristics of wheat are kept separately from the information in the wheat reactor. The growth of any wheat-like plant could be simulated in this reactor once its necessary growth characteristics are entered into the database. Some other plants such as tomatoes where the fruit are harvested continuously without killing the plant are even more complex to model and will require a different type of biomass reactor.

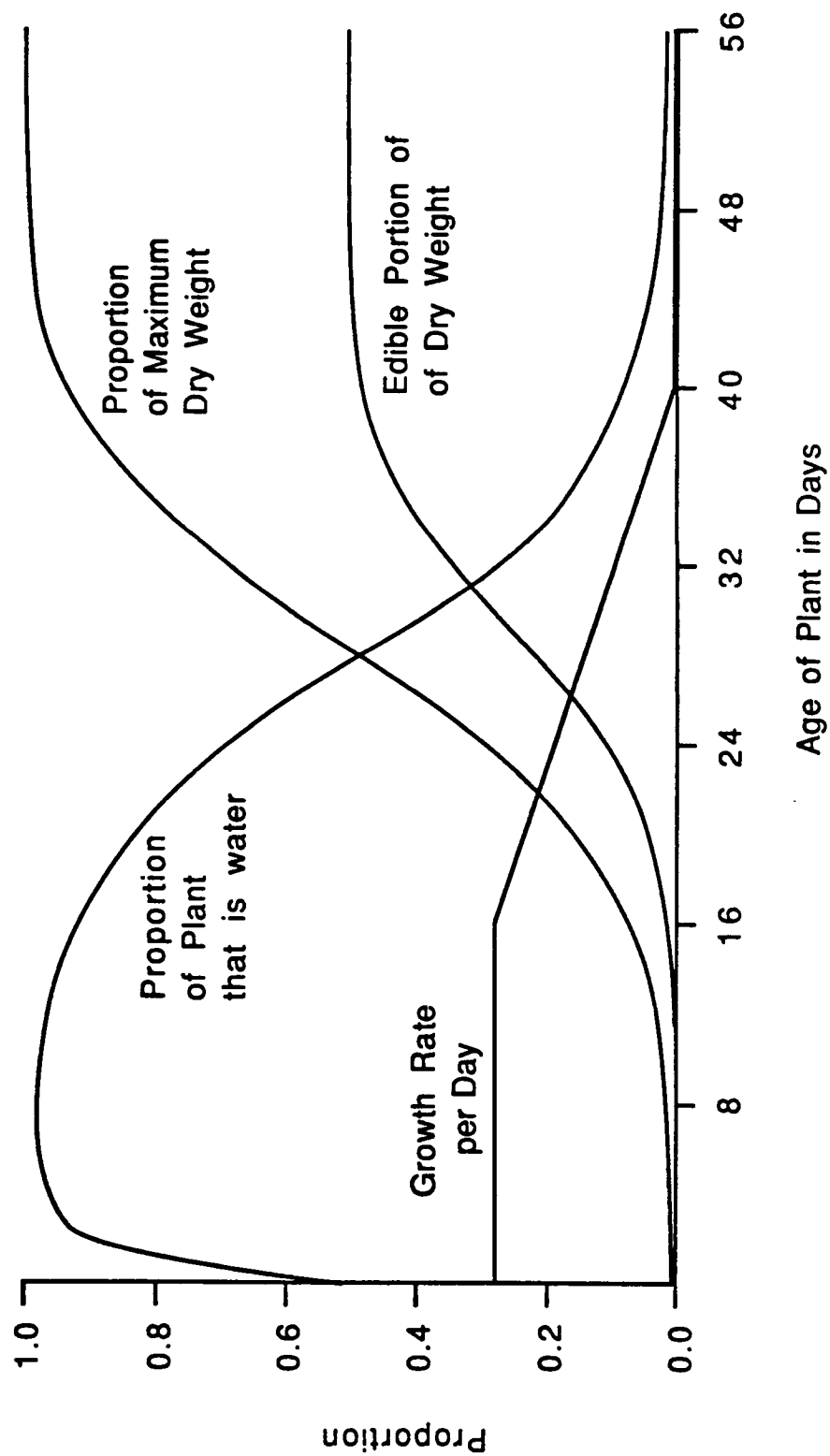
Wheat Growth Parameters

Figure 2.5 shows several growth and other characteristics of wheat as they are represented in the crop plant database. All of these parameters except proportion of maximum dry mass are represented in the model as lists of 55 numbers each, one for each day of age. Other growth characteristics are constant or depend on dry weight of the plant such as transpiration and respiration. Wheat transpiration was set at .05 grams of water per gram of plant per minute. Since it depends on light intensity no water is transpired during the dark cycle. The respiration rate is set at -.00008 grams per gram of plant per minute. Both transpiration and respiration depend on the percent of water in the plant. Dry plants don't transpire or respire.

Photosynthesis

The photosynthetic rate of plant production varies from .0003776 grams of new plant material per gram of plant per minute for very young plants to zero for plant 40 days or older. This figure was chosen so that a young plant exposed to 16 hours of 100% intensity light with the above respiration rate would grow 28% in one day. For a given time-step the respiration rate is added to the photosynthetic rate to calculate the net growth of the plant. During the dark part of the cycle plant mass is actually lost: about 4% for young plants. The curve for proportion of maximum dry mass in figure 5 is actually calculated from the age dependent minute growth rates starting with a seed of .1 gram iterated in 10 minute intervals. The vector is not carried as a part of the plant characteristics and actual growth may vary according to the duration of the light period, light intensity and CO₂ availability.

Figure 2.5: Growth Characteristic of Wheat in LSS-2



Planting and Harvest

While wheat is grown continuously it is aged once a day. What this means is that the dry mass of a single plant of each day of age is carried in a list associated with the wheat reactor. The number of each age of plants is carried in a separate vector. During a single day as the plants grow, each of the age-specific masses is increased. Then once a day the numbers in the mass and age lists are moved over one space. The numbers at the end of the lists, representing 55 day old plants, are used to determine how much wheat is harvested. The first number of each list represents the number of seeds planted and the mass of a single seed. Varying planting regimes can be simulated by varying the number of seeds planted each day. Death of plants and growth stunting diseases such as wheat rust can easily be incorporated into this representation of crop plants.

Gas and Nutrient Cycling in Wheat Reactor

The size of the plant growth chamber is currently set at 8000 liters. Gases are taken directly from the crew cabin and returned there after removing excess water vapor. No facilities for supplementing the CO₂ concentration directly from the CO₂ tank are currently provided. Water is stored in a separate nutrient tank from that used with the algae reactor and cycled continuously through the wheat reactor. Adjustment of water level, ammonia concentration and nutrient salts is done by the wheat nutrient mixer. The wheat reactor and other reactors, stores, and pipes in the wheat subsystem have been implemented but the LSS-2 configuration has been neither debugged nor calibrated. Time dependent graphs of gas concentrations during the transition period therefore cannot be shown.

LSS-3: PLAIN CONFIGURATION

While the plain configuration, LSS-3, has no plant subsystems, it is hardly simple. In this section, therefore, the non-plant subsystems will be described in greater detail. The reader should be reminded that the components described here are also integral parts of the other two configurations.

Major Subsystems

Three major subsystems comprise LSS-3. The first is the crew cabin and the crew members themselves. The second is the RITE waste disposal system which is modeled more or less after the one built by General Electric and given to this university. The interface between the crew cabin and the RITE system, namely the commode, urinal, paper/plastic shredder and crew washer, can be thought of as belonging to either subsystem, but will be included with the latter if only for convenience in discussion. The third is a collection of reactors designed to remove water vapor and CO₂ from the cabin air, split water into H₂ and O₂ and inject the latter back into the crew cabin as needed.

CREW SUBSYSTEM

The Crew Cabin

The crew cabin is the largest store in the GENERIC LIFE SUPPORT SYSTEM. It is envisioned as containing 60,000 liters of gases at STP. Initially there are 17,900 grams of O_2 , 58,464 grams of N_2 and 35 grams of CO_2 . These concentrations are close to those on earth. All other subsystems interconnect with the crew cabin.

Crew Members

The crew members themselves are the most complex reactors. They are each composed of seven compartments, most of which are used for input and output. The lung is modeled as two compartments, one for taking cabin gases in and exchanging O_2 , CO_2 and water vapor with the blood compartment and the other for taking the resulting gases back to the cabin. The stomach takes in food and water, passes some to the colon and allows the rest to be absorbed into the blood. The colon outputs unabsorbed food into the commode. The bladder receives water and urea from the blood and outputs them into the urinal. The sweat compartment takes water out of the blood and returns it as water vapor to the cabin. Metabolism of food takes place in the blood.

Food and Water Regulation

The blood volume is kept within about 200 mls of 5 liters by a thirst routine. Blood amounts of metabolizable foods are regulated by a hunger function which allows the crew member to eat more or less than a regulation meal according to how much energy reserve the crew member has. Snacks are allowed only in extreme emergencies and consist mainly of simple carbohydrates. Urination, defecation, washing and eating are modeled as scheduled point events. The start and stop time of sleep and work are also part of each crew member's schedule.

Crew Energy Requirements

Each crew member has a basal metabolic rate which is used to calculate his or her current metabolic rate which depends on what the crew member is doing. For example, sleeping results in a metabolic rate which is 80% of basal while working hard boosts it to 130% of basal. The current metabolic rate is used to calculate energy consumption and thus gas uptake and output as well as the breathing rate and therefore water loss through the lung. Logically it should also affect sweat rate. We are working on this aspect.

RITE WASTE DISPOSAL SYSTEM

Crew-Waste Disposal Interface

Four simple reactors and their four storage tanks comprise the interface between the crew members and the waste disposal system. The urinal takes in a crew member's urine water and urea along with some air from the cabin and a liter of water from the used wash water store. The air is separated out, sent through a sterilizer and returned to the cabin. The liquid is stored for later input into the evaporator. The commode receives feces from the crew members, mixes it with water and stores it in the slurry tank for input into the evaporator. The shredder receives paper, plastic and plant waste materials, mixes them with used water and stores the mixture in the garbage tank. The crew washer serves all washing functions which in reality would take place in separate reactors. Mostly it takes water from the water store and mixes it with a generic soap and stores it for use in the other three disposal reactors, and for direct input into the evaporator.

The Evaporator and Incinerator

The evaporator is loaded according to a schedule. Four times a day starting at 3:00 am the evaporator is loaded with stuff from the four disposal tanks. Air is drawn off, sterilized and returned to the cabin. Water evaporates at a rate dependent on the concentration of the slurry and is drawn off. The concentrated slurry is packed into the waste shuttle to be loaded into the incinerator which is also run on a fixed schedule. Water vapor from the evaporator and combustion gases from the incinerator are first sent through a pyrolysis unit which kills any organisms floating off from the evaporator and catalytically converts NO_2 and other noxious nitrogenous combustion products into more acceptable gases. After the pyrolyzer the gas stream goes through a water condenser and then through a CO_2 remover before being returned to the cabin. Under normal operation this gas stream consists mainly of water and CO_2 so very little gas makes it back to the cabin. The incinerator is injected with 80 grams of pure O_2 every half hour until there is no more stuff to combust. As mentioned above, the combustion products of each compound are stored in the compounds database. Non-combustable solids are stored as ash.

AIR PURIFICATION AND REGENERATION

CO_2 and Water Removal from Cabin Air

The third subsystem in the basic configuration is really all the reactors not already discussed but which happen to collectively serve the function of gas conversion without the use of plants. A rather rapid stream of air is drawn off from the cabin and has the CO_2 removed in an electrochemical depolarization (EDC) unit which is described elsewhere. Essentially it is a hydrogen fuel cell which is hydrogen limited and serves to facilitate the dissolving of CO_2 into the water at one pole and driving it out of solution at the

other. Water and electricity are made in the process. The gas stream next enters a condenser where the water vapor is removed. Finally the stream enters a nitrogen remover which is really a part of the algae and wheat subsystems where a side stream is drawn off and the N_2 purified by catalytically removing the O_2 in the presence of hydrogen. The CO_2 from the CO_2 remover is sent to the CO_2 store and the water from all three is sent to the water store.

Bosch Reactor and Electrolyzer

Hydrogen for the N_2 remover and for all of the CO_2 removers is made by electrolyzing water. The resulting pure O_2 is stored in the O_2 storage tank until needed by the incinerator or to supplement the crew cabin. Hydrogen is also used by the Bosch reactor to reduce excess CO_2 to elemental carbon which is simply stored. The resulting water is sent back to the H_2O store.

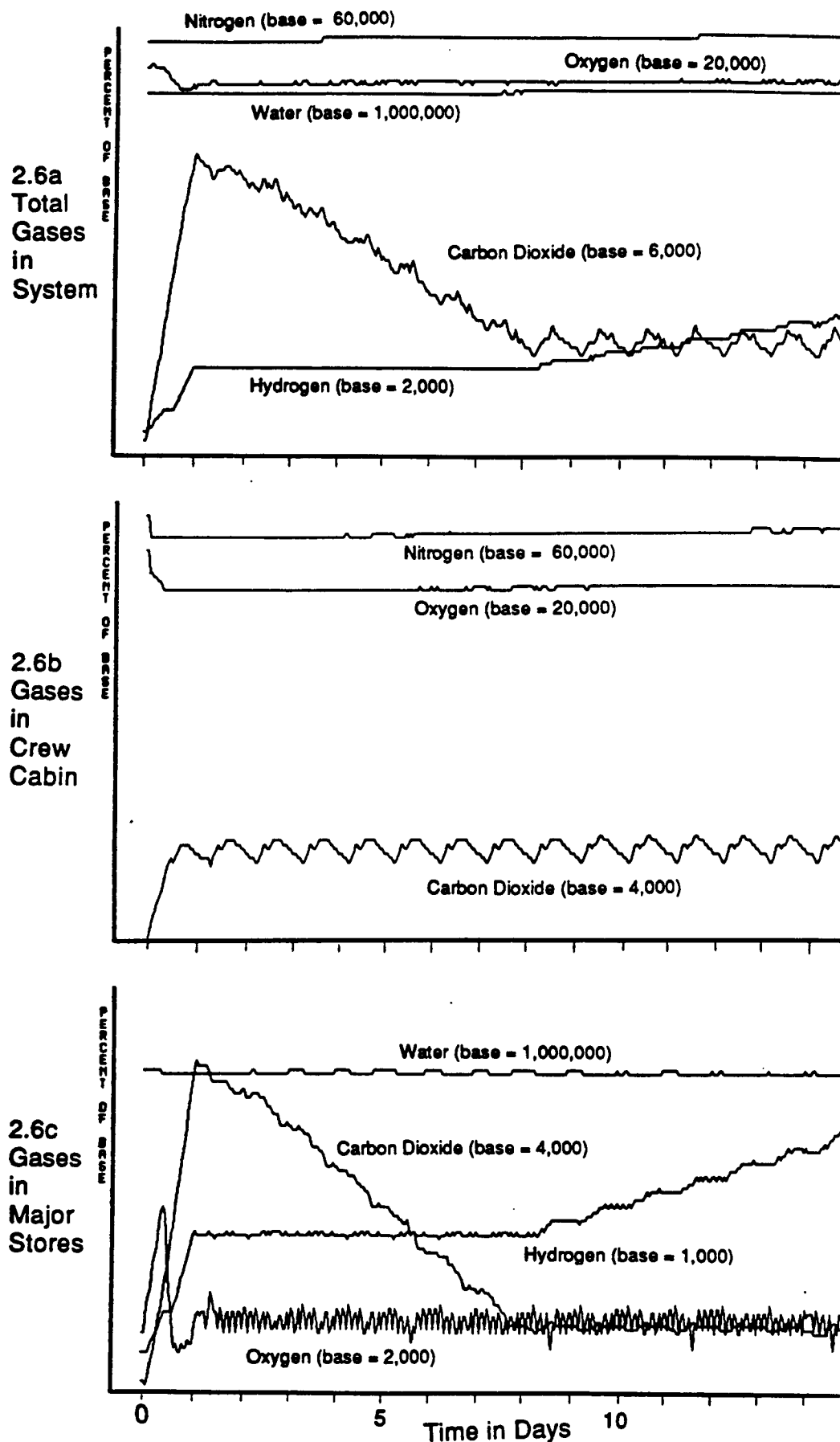
Chemical vs Biological Reduction of CO_2

The gas regeneration functions of the electrolyzer and the Bosch reactor are duplicated in the LSS-1 and LSS-2 configurations by the plant reactors themselves. However, as long as the grown food comprises only a part of what is eaten by the crew members, food production will not be adequate to regenerate all the gases used by the crew. In addition, the chemical gas conversion system is useful in fine tuning the gas balance between the crew cabin and the CO_2 and O_2 storage tanks. The optimal conditions for growing plants must be maintained and so the gas mixtures in the plant reactors cannot be manipulated to suit the conditions in the crew cabins or to regulate the amounts in the storage tanks. Therefore chemical converters will always be needed for backup, emergencies and regulation.

COMPARISON OF SIMULATION RUNS BETWEEN LSS-1 AND LSS-3.

LSS-3 Simulation Results

Figures 2.6a through 2.6c show the relative levels of the four major gases and water over time starting with the same initial conditions as in the base runs for LSS-1 discussed above and in figure 2.4a - 2.4c. The levels of gases overall, in the crew cabin and in storage are quite similar in the two runs. The major exceptions are carbon dioxide and hydrogen. In LSS-1 carbon dioxide remains high for a relatively longer period of time while hydrogen remains nearly constant. In LSS-3 the carbon dioxide falls off to a steady state cycle after about eight days after which the hydrogen begins to rise. This would also probably occur in LSS-1 if the simulation were continued for a longer period of time. Interestingly, carbon dioxide in all three places and oxygen in the O_2 store show daily cycles. The x-axis hatch marks denote 12 midnight so the low period for CO_2 is just before 6 am when the crew wakes up. Although the cycles for LSS-1 and LSS-3 are nearly identical in shape, the CO_2 values in the crew cabin are 10% lower in LSS-1 due to the removal of CO_2 by the algae.



Comparison of Bosch Usage With and Without Algae Reactor

During the 14 day runs of LSS-1 and LSS-3 the use of the electrolyzer and the Bosch reactor were also sampled. They are shown in Figures 7 and 8, respectively. In LSS-1 CO_2 is partly converted into edible algae while in LSS-3 it is reduced to elemental carbon. After 14 days 11.57 kilograms of carbon had accumulated in the Bosch reactor for LSS-1 compared to 13.68 kilograms for LSS-3, an increase of over 18%. The amount of algae grown during this period is about 8,316 grams, 21% or 1736 grams off which is carbon. Thus, 82% of the carbon not being reduced by the Bosch reactor in LSS-1 is being incorporated into algae. The remainder is still in the form of CO_2 in the CO_2 store. The amount of food taken from the carry-on food stores is the same in both configurations and so is the amount of CO_2 produced by metabolism and combustion in the incinerator. The electrolyzer was also used more in LSS-3, an increase of about 10% over LSS-1.

THE FUTURE

Object-Oriented Front End

The future of the generic life support system with its simulation capabilities is at a cross-roads. Plans have been discussed to abandon the simulation aspects of the knowledge base and convert the structure into a front end management package to use in conjunction with a mathematical program that solves simultaneous differential equations. The latter are more useful to engineers because of their precision which is needed for designing chemical systems and process simulation and modeling transient processes *e.g.* start-up. Although most of these mathematical packages have been around for up to 20 years, very little work has been done recently to increase their utility by making the input functions and file manipulations more automatic. A real need exists to build a model management system similar in structure to the generic life support system but without its time-step simulation capabilities which can intelligently augment the system engineer's ability to use the existing mathematical packages. Having built the time-step simulation version of the generic life support system, it is easier to envision how such a model management front end knowledge base could be built. Such a front end program would not be specific to modeling life support systems but could conceivably be useful for any complex problem involving the repeated simultaneous solving of sets of differential equations.

The Object-oriented Time-Step Simulation Model

The development of a dynamic simulation program need not be the death-knell for the time-step simulation portion of the generic life support system. Even though it is less precise it is much more visible and accessible to the common person than the sophisticated mathematical programs with or without knowledge based front ends. For example, the simulation driver could be interactively put into stepper mode in the middle of the run. This would allow the user to step through the routines one at a time in

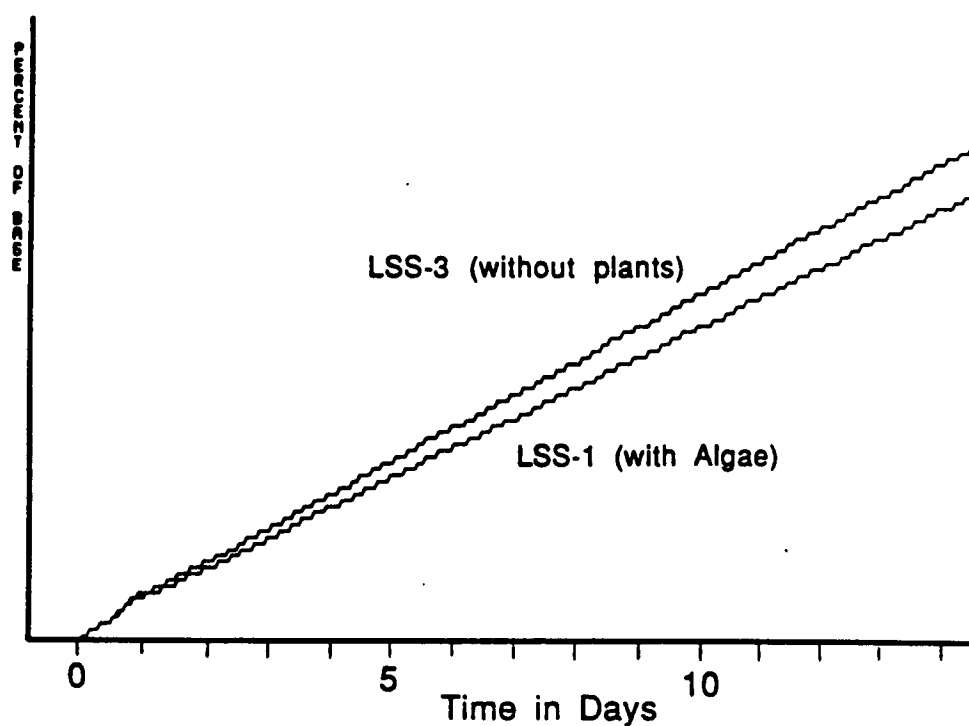


Figure 2.7 Relative use of Electrolyzer in LSS-1 (with Algae) and LSS-3 (without plants)

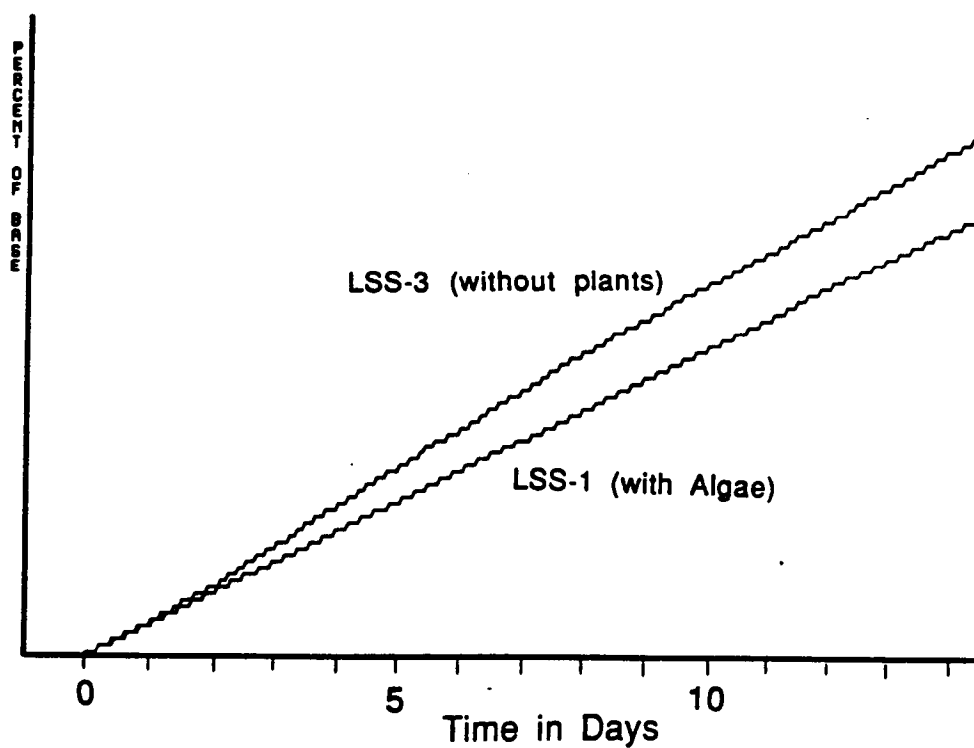


Figure 2.8 Relative use of Bosch reactor in LSS-1 (with Algae) and LSS-3 (without plants)

order to watch how each affects the displayed variables. If a set of variables, such as the gases in the crew cabin which is stored in the cabin object's contents.vector slot, are not being displayed through active images they could be displayed temporarily in a KEE output window. As the simulation is stepped through under the user's control, the window would darken whenever the variables change. By noting which routine is being executed, the source and amounts of gases affecting the mixture in the crew cabin could be isolated. It is significant that this interaction and scrutiny can take place without any reprogramming nor even interrupting the course of the simulation. When the user has finished his investigations he simply puts the simulation driver back into automatic mode and calculations resume.

SECTION II

MODELING

Chapter 3

A PRELIMINARY COMPARISON OF CELSS CONCEPTS

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Chapter 3

A PRELIMINARY COMPARISON OF CELSS CONCEPTS

INTRODUCTION

Keeping humans alive in space requires attention to a number of factors usually taken for granted on the Earth's surface. We expect natural systems automatically to provide breathable air, to supply edible and nutritious food, to provide drinkable water, and to aid in disposal of wastes. In space, specific plans must be made for provision of these requirements. On all U.S. space missions to date, oxygen, water, and food have been stowed onboard prior to launch and gradually consumed during flight. Wastes generated during a mission have been stored for disposal after landing. But as plans are developed for advanced missions (Lunar Base, Mars fly-by, Mars Base), new approaches to air, water, food, and wastes must be taken. As crew numbers increase and mission durations lengthen, the weight of air, water, and food which would have to be launched becomes prohibitive.

Recycling of wastes and regeneration of air and water can be accomplished using physico-chemical technologies. A chemical approach to food synthesis, the so-called formose reaction,⁵⁷ has been explored but has been less successful. The formose reaction chemically synthesizes sugars from CO and H₂. But since the reaction produces equi-molar amounts of the D and L isomers, and since organisms such as humans can utilize only the D isomers, a maximum of 50% of the product would be biologically active. Because a wide variety of sugars are formed, including some which are indigestible by humans, even less is available. Furthermore, certain toxic compounds, such as formaldehyde, are formed in side-reactions. Feeding studies with rats have shown that when 40% of the diet is supplied by formose sugars, diarrhea and death occur.⁵⁸ It thus appears that no process other than a biological one is presently available to synthesize food. Food can only be produced by growing organisms. This being the case, we must select the best organisms and learn how best to grow them.

A number of organisms for food production have been studied: higher plants,^{59,60} algae,⁶¹⁻⁶³ hydrogen-utilizing bacteria,^{64,65} and methanol-utilizing bacteria.⁶⁶ Most attention has been devoted to higher plants and algae. Higher plants have the advantages of familiarity, palatability, and reasonably well-defined growth requirements. In addition, processing techniques for higher plants are well-developed so that virtually all of the human diet can be supplied by higher plants. Unfortunately, higher plants take up a great deal of volume and usually produce a significant fraction of their total biomass as inedible material (stems, husks, etc.). Because of the species-specific architecture of higher plants, it is sometimes difficult to deliver necessary light levels to them efficiently, so if electrical lamps are used to supply

light, power requirements are high. Algae (and bacteria) have the advantages of extreme compactness, ease of handling and high production efficiency. Their requirements for growth are also well-defined. Algae are usually grown in bioreactors which are almost as compact and convenient as chemical reactors. Unfortunately, processing techniques to convert algae into palatable, nutritious food are just now being developed. Neither algae nor higher plants are suitable in their raw state for a large fraction of the human diet.

Prior to actual construction of equipment which incorporates various approaches to CELSS, it is desirable to model the system so intelligent choices may be made. A number of CELSS modeling approaches have been taken in the past. Volk and Rummel⁶⁷ developed a steady-state stoichiometric model of a life support system which included a higher plant (wheat) to regenerate food and oxygen. Carbohydrates, fats, protein, fiber, and lignin were represented by model compounds. The model included 24 linear stoichiometric equations with 44 unknown coefficients which could be solved by imposing constraints. Regeneration of oxygen was provided solely by photosynthesis. Averner has also taken a stoichiometric approach to CELSS modeling.⁶⁸ Hall, *et al.*^{69,70} analyzed a number of technology options and processes which might be used for life support systems on the U.S. Space Station, and recommended specific processes or equipment items for a number of operations. These recommendations were based on comparisons of cost, weight, power requirements, reliability, etc. Other authors have used dynamic models to understand the response of CELSS to component failures and to devise control strategies.^{71,72} Dynamic models can be extremely complex and difficult to solve.

The focus of this section of the report is to model the stoichiometry of a life support system which includes a bioreactor containing higher plants and/or algae to accomplish regeneration of part of the food and oxygen, as well as several physico-chemical systems which accomplish air regeneration, water purification, and waste processing. It is a steady state model which calculates flow rates for the various operations, so size requirements for equipment components can be estimated. Details of the model are given in the Appendix.

As indicated in Fig.1, this CELSS design incorporates a bioreactor containing higher plants and/or algae, which produces part of the food and oxygen needed by the astronauts. Additional food requirements are supplied from food stores. Additional oxygen is provided by electrolysis of water. Hydrogen produced in electrolysis is used to reduce carbon dioxide, a reaction which yields water. Waste materials (feces, urine solids, and trash) are combusted to yield carbon dioxide, water and nitrogen gas (it is assumed that any NO_x produced in the combustor is catalytically converted to N_2). Water from urine is purified and made potable. (Wash water is not considered in this analysis although the GE RITE System is sized to include wash water.) Cabin air is purified to remove moisture, carbon dioxide, and excess N_2 . Storage tanks hold food to be provided as needed; other such tanks also allow wastes (H_2 , CO_2) to accumulate before processing, and damp out surges in H_2O and O_2 flows. The water and oxygen tanks can also be sized to provide emergency stores in case of equipment failure.

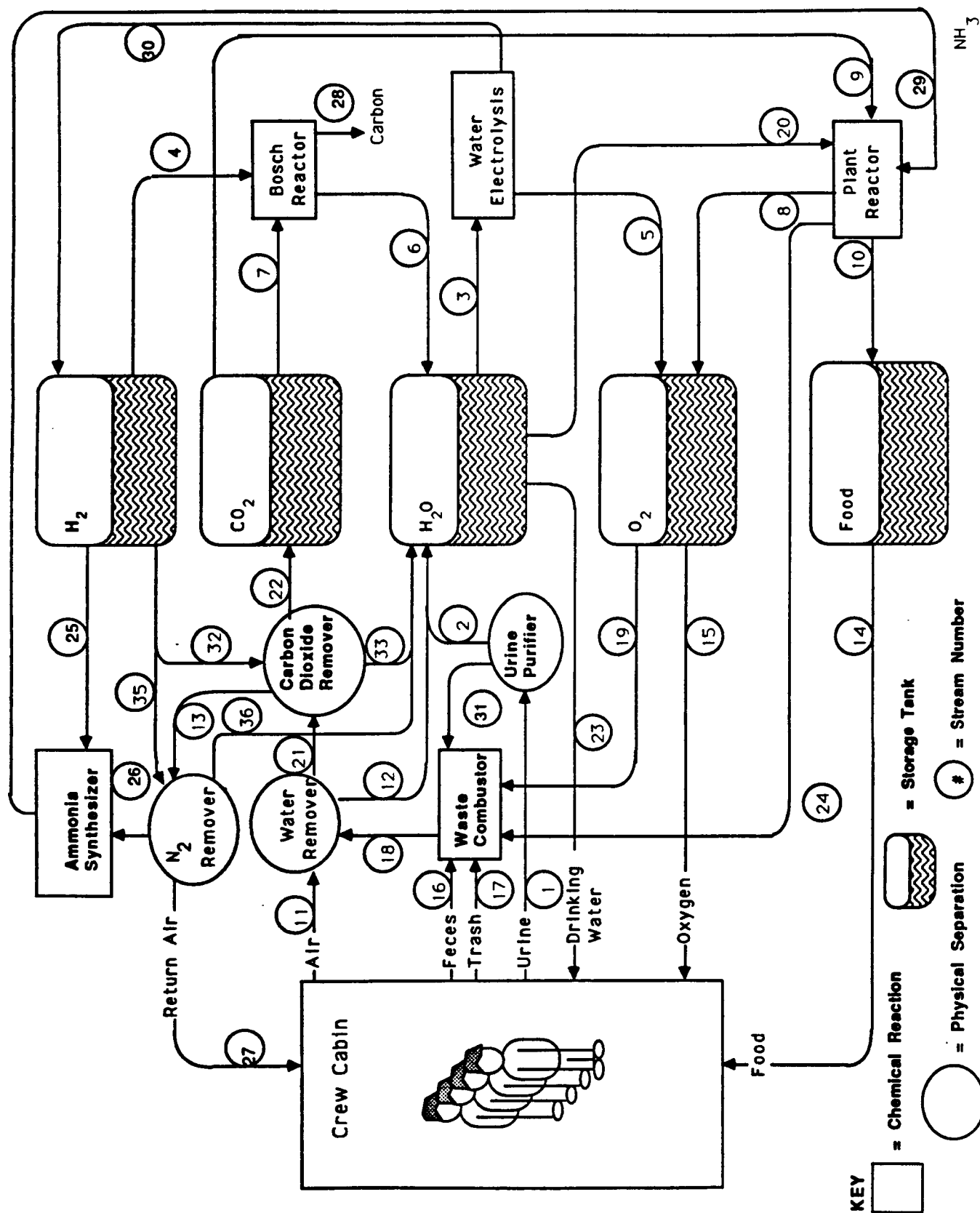
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Figure 1. CELSS schematic using higher plants or algae for food and oxygen production.

EQUIPMENT SELECTION

Table 1 compares various options for hardware to accomplish the operations described in Fig. 1. Based on the characteristics of each option, specific equipment items were chosen to perform each unit operation described in the model. These choices are described below.

Waste Combustor/Urine Purifier

The RITE (Radioisotopes for Thermal Energy) System, developed in the 1970's by General Electric, was selected since this single unit carries out two functions; waste combustion and urine purification.¹ The RITE System has performed successfully during 180-day tests of continuous operation, so it can be regarded as a well-developed piece of equipment. All wastes from the crew cabin (feces, urine, trash) are placed in the RITE System. Water is recovered by evaporation and condensation. Dried solids are combusted to produce CO₂ and H₂O. Heat for evaporation and combustion is provided either by radioisotopes or by a resistance electrical heater. Some oxides of nitrogen (NO_x) may also be produced in combustion. It is assumed that these are converted to N₂ and H₂O via a catalyzed reaction with ammonia.² Because the NO_x yield is unknown, the ammonia requirements for this purpose cannot be calculated at this time.

Water Removal

Water vapor from three sources must be condensed to the liquid phase. These three sources are evaporated water from the RITE System, water produced by combustion in the RITE System, and water from the crew cabin atmosphere (which has evaporated directly from the astronauts). Direct condensation was selected since it is based on well-developed technology. Waste heat radiators in spacecraft typically operate at -15.6° to -2.8°C³ so a refrigeration system should not be required. For a microgravity environment, the condenser surface must be fitted with wicks to remove the accumulated water.

Carbon Dioxide Remover

Membranes and the solid amine adsorber are also promising technologies for CO₂ removal. However, the electrochemical depolarizer has been recommended by Hall, *et al.*⁴ The depolarizer is actually a fuel cell which runs on hydrogen and oxygen.

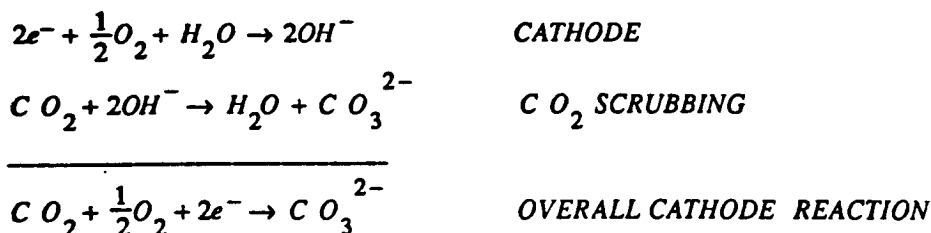
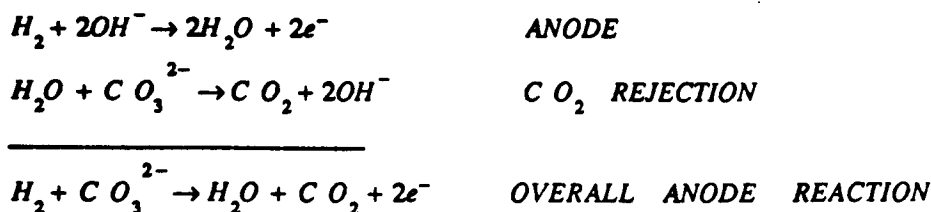


Table 1. Options for Life Support Equipment

Function	Option	References	Advantages	Disadvantages
Waste Combustor	Combustion	1,20,21	Simple Well understood	Creates NO_x
	Supercritical Water Oxidation	21,22	Converts most toxins	Creates N_2O
	Electrochemical Oxidation	23,24	Low thermal load	Poorly understood
Urine Purifier	Distillation	25	Simple	Volatiles not removed High heat requirement
	Evaporation	26	100% recovery	Replace wicks
	Vapor Compression	27,28,29	Less Energy than distillation	Complex equipment
	Reverse Osmosis	30,31	Very low energy	Replace membranes
	Activated Carbon	32	Simple	Losses upon regeneration Salts not removed
	BioChem Fuel Cell	33	Creates energy	Not fully developed
Water Separator	Direct Condensation	3	Well understood	Needs complex mechanical equipment or large radiator
	Absorbents (e.g., silica gel)	35	Regenerate with waste heat	Heat transfer difficult, requires regeneration, still need H_2O condensation for recycle
Carbon Dioxide Separator	Electrochemical Depolarizer	36,37	Fuel cell does not require H_2O removal	Additional burden on electrolytic cell, requires H_2O
	Solid Amine Absorber	2,38	Does not require H_2 or H_2O removal	Requires recycle, multi-cell
	Cryogenic Condensation	39		Needs complex equipment or large radiators
	Molecular Sieve	35	Regenerate waste heat	Requires energy for recycle

Table 1. Options for Life Support Equipment - Continued.

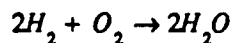
Function	Option	References	Advantages	Disadvantages
Nitrogen Separator	Lithium Hydroxide	3	Simple	Not reversible
	Membrane	5	Low energy, low heat rejection	Not developed technology
	Membrane	55	Low energy, low heat rejection	Not developed technology
	Cryogenic	39		High energy
	Pressure Swing Adsorption	56	Low temperature, very efficient	System weight
	Temperature Swing Adsorption	53	Low pressure	High energy, high heat rejection
Ammonia Synthesizer	Hilsch-Ranque Tube	34	Simple	High energy
	Remove Oxygen by Combustion of Hydrogen	41	Very Simple	Consumes hydrogen
	Haber Process	5	Well understood	High pressure
Water Electrolyzer	Biological	43	Low pressure Low temperature	Light needed High energy Complex support equipment
	Spark Discharge	44	Low pressure	Low yields, N_2H_4 side reactions Unproven technology
	Static Feed Generator	45,46,47	Can use impure H_2O source, e.g., wash, urine	Complex control strategy
Carbon Dioxide Reduction	Solid Polymer	48,49		Requires pure H_2O
	Sabatier	50,51	Catalyst stays active	Complete closure not possible
	Bosch	50,51	Complete closure is possible	Catalyst deactivation Reaction efficiency
	Sabatier/Pyrolysis	52	Complete closure is possible	2-step process



The carbon dioxide is adsorbed in the cathode section where it is converted to carbonate which is soluble in the liquid electrolyte. The carbonate-laden electrolyte is then placed in the anode section where the carbonate is converted back to CO_2 and released. Electricity is produced by this process.

Nitrogen Remover

The simplest and most effective method of obtaining relatively pure nitrogen from the circulating stream of cabin atmosphere is to remove the oxygen catalytically by the addition of hydrogen.



Ammonia Synthesizer

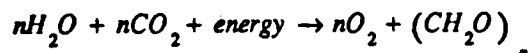
Holtzaple has described a conceptual design for a Haber-type ammonia synthesizer which operates at $370^\circ C$.⁵ Because the operating pressure is very high (4000 atm), the unit achieves virtually 100% conversion. Such high pressures are relatively easy to accommodate because the reaction chamber is very small.

Water Electrolyzer

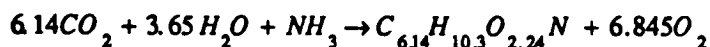
The static feed generator has been recommended by Hall, *et al.*⁴ and hence is chosen as the preferred method of electrolyzing water.

Higher Plant/Algal Bioreactor

Bioreactors for cultivation of algae have been extensively studied; characteristics of a number of designs have been reviewed by Miller and Ward.⁶ Additional studies have subsequently been reported^{7,8} but the essential conclusions reached by Miller and Ward remain valid. All such reactors depend on the same fundamental process, namely oxygenic photosynthesis. Although photosynthesis actually consists of several dozen partial reactions occurring in sequence, it can be summarized as



where $(CH_2O)_n$ represents carbohydrate such as might be used for food. Energy is supplied as visible light ($\lambda=400-700nm$). In fact, the above equation is an oversimplification since the final product of photosynthesis by algae is more algal cells. Because algal cells are not 100% carbohydrate, but contain other reduced organic molecules as well, there is not a 1:1 stoichiometry between CO_2 uptake and O_2 production. Therefore, a more accurate chemical equation should be used to describe the overall process of the bioreactor:



Even this equation is incomplete, since growing algae cells also incorporate sulfur, phosphorus, potassium, iron, manganese, and approximately 10-15 other elements. But carbon, hydrogen, oxygen, and nitrogen account for 96-98% of the mass of algal cells, and therefore the above equation accounts for virtually all the algal biomass accumulation.

Algal bioreactors originally appeared attractive as components of regenerative life support systems because of their gas exchange capacities, i.e., removal of CO_2 from cabin atmosphere and replenishment of O_2 . Early studies focused on this function. But it was recognized early-on that such gas exchange is accomplished only as a by-product of biomass production. That is, CO_2 removal and O_2 release are stoichiometrically coupled to accumulation of algal cells. Unless these algal cells are consumed by the astronauts, they represent an ever-increasing mass of waste product which must be stored. In such a case, food stores would gradually be exchanged for stored algal biomass. The same analysis applies to any photosynthetic organism which is not completely consumed in astronaut diets. Only that fraction of biomass production which can be eaten by the crew represents a net contribution toward closure of the system with regard to O_2 . In order to approach complete closure of a regenerative system, it is necessary that the algae form at least part of the astronaut diet. It is therefore necessary to consider whether algae are suitable as human food.

Algae in almost their raw, unprocessed state have been included in the diets of various primitive peoples for hundreds if not thousands of years.^{9,10} There was therefore some reason to believe that raw algae might be suitable for astronaut consumption. But laboratory studies in which rats, chickens and human volunteers were fed algae in various proportions of the diet have not borne out the earlier optimism. Although extensive studies on the long-term effects of algae feeding on humans have never been carried out, it is generally believed that raw algae are not suitable for providing 100% of the human diet. One of the earliest careful studies with humans was carried out by McDowell and co-workers.^{11,12} These investigators concluded that humans could tolerate up to 100 gms of algae per day in the diet. In that study, 100 gms of algae per day supplied slightly more than 50% of the protein intake and approximately 20-25% of the total calorie intake. Investigations such as these, and others carried out by Japanese researchers, have led to the general conclusion that unprocessed algae (or algae that have only

been heat-dried) can contribute a maximum of about 50% of the human diet.¹³ Consequently, increasing attention has been paid in recent years to processing techniques for algae which would make them more palatable and nutritionally suitable for human consumption. Waslien and Steinkraus¹⁴ and Averner, *et al.*¹⁵ reviewed some of the features of raw algae which detract from their suitability as a human dietary staple. More recently, Karel¹⁶ described post-harvest processing techniques which offer promise of converting algae biomass into a nutritionally satisfactory human diet. If this can be done, algal products might contribute a larger portion (approaching 90-100%) of the diet.

Humans engaged in moderate to strenuous activity will require approximately 600 L of O₂ per 24 hrs. It has been demonstrated¹⁷ that for a wide range of algal species and culture conditions, production of one liter of oxygen (at standard temperature and pressure) is accompanied by production of approximately one gram of algal cells. Therefore, if the algal bioreactor is to supply all the oxygen requirements for one person, it must have a production capacity of 600 grams of algal biomass per 24 hrs. Miller and Ward⁶ evaluated production rates from several different bioreactor designs, and estimated the volume of algal culture needed to support one person with each design. Estimates of volume requirements ranged from 3.5 liters to 3000 liters, depending primarily upon the configuration of illumination. Assuming a productivity of 8.88 g/L d, the volume would be 68 L per person or 270 L for a four-person crew.

An alternate approach to sizing the algae reactor is to use the model presented in the Appendix. Assuming the average metabolic load is 135W, a four-person crew must consume 3.55 kg algae/d if all their metabolic needs are supplied by algae. Assuming the reactor productivity is 8.88 g/d L, then a 400-L reactor would be required. This will be chosen as the reactor volume to provide a more conservative estimate of the required volume.

To perform weight trade-off studies, it is necessary to estimate the weight of a 400-L bioreactor which is sufficient for a 4-person crew. Flight-ready algae reactors have not yet been developed.¹⁵ Even for ground-based reactors which have been described in published literature, total system weight has rarely been reported. We therefore must estimate the weight of the bioreactor.

A schematic of the algae reactor is shown in Figure 2. This algae reactor has tubular light pipes which are supplied with light from an artificial source or the sun. Mori¹⁸ has proposed a similar light delivery system. A concentrator is used to focus the light onto the light pipes. A diffraction grating may be used to isolate only those wavelengths which are useful to the algae. By separating the light source from the algae, the waste heat from the light is rejected at a high temperature rather than a low temperature which minimizes the area of the waste heat radiators. The diffraction grating will also lessen the load on the waste heat radiators. The aqueous suspension of algal cells will be recycled through the algae reactor with a fairly high velocity. The cell suspension exiting the reactor will go through a cyclone to separate oxygen. The stream is then split. Most of it goes through a heat exchanger to remove waste heat. The smaller stream goes through a tangential flow membrane separator to recover algae

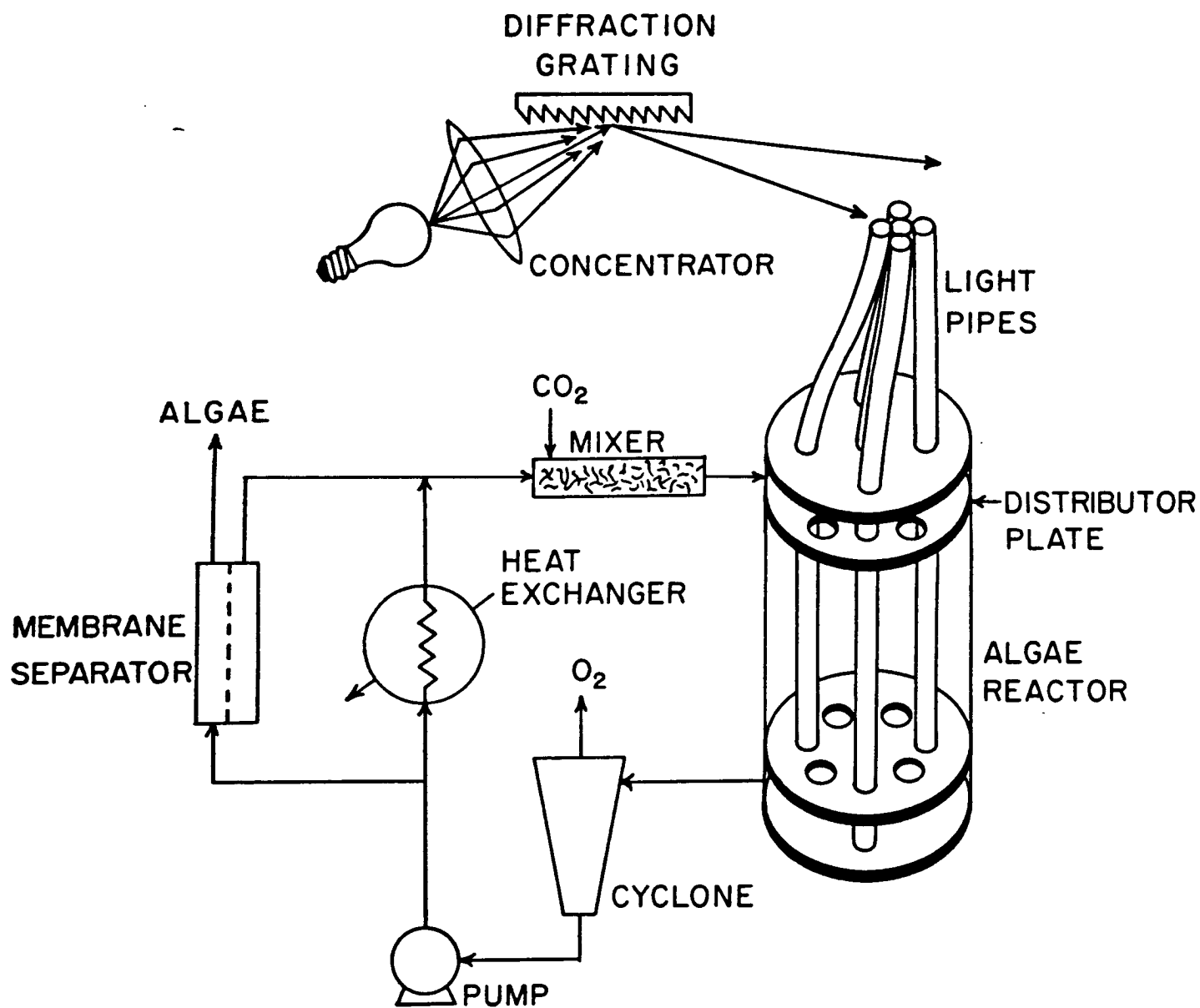


Figure 2. Schematic of algae reactor.

product. Carbon dioxide is introduced into the recycled liquid and is mixed with an in-line mixer. Table 2 shows weight estimates for each of these major components for a reactor which would support a four-person crew.

Table 2. Weight estimates for a 400-L. algae reactor.

	Weight (kg)
Reactor Vessel	400
Liquid	400
CO ₂ In-Line Mixer	20
O ₂ Cyclone Separator	30
Diffraction Grating	10
Light Concentrator (Fresnel Lens)	10
Tangential Flow Membrane Separator	30
Light Source	20
Heat Exchanger	50
Pump	30
Control Equipment	30
	1030

Higher Plant Reactor

The growth of higher plants in space is difficult. A conceptual design for a higher plant reactor has been developed by Boeing. (For more details, see Section III Chapter 11 of this report.) The reactor weighs 218.7 kg per square meters of growing area. This reactor provides the basis for our weight estimates. It was assumed that Irish potatoes were grown in the reactor. They have a productivity of 29.49 g/m²d.

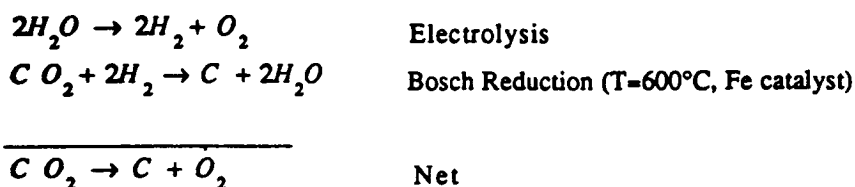
Artificial Chloroplast

An "artificial chloroplast" is a concept for food synthesis which requires no light energy. It is described in more detail in Section III Chapter 8. In the artificial chloroplast, energy for food synthesis is provided directly from electricity instead of light. Algae and higher plants require light energy. Because the conversion from electricity to light is only about 20% efficient and the photosynthesis process is only about 3% efficient, the artificial chloroplast offers significant potential for energy savings compared to higher plants and algae.

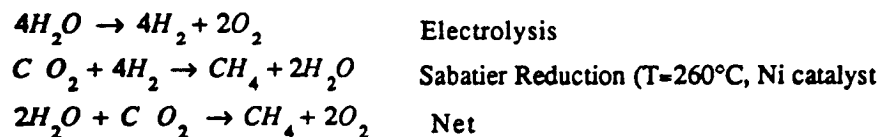
Carbon Dioxide Reduction

The two technologies commonly considered for carbon dioxide reduction are the Bosch and Sabatier reactions. Although they are generally considered interchangeable, in fact, they are not. The Bosch reaction will always allow complete regeneration of oxygen while the Sabatier allows closure only if the food and trash are highly oxidized. This is explained further.

Both the Bosch and Sabatier systems require that water be split electrochemically to produce hydrogen and oxygen. The hydrogen is used to reduce carbon dioxide. In the Bosch reactor, the products are carbon and water.

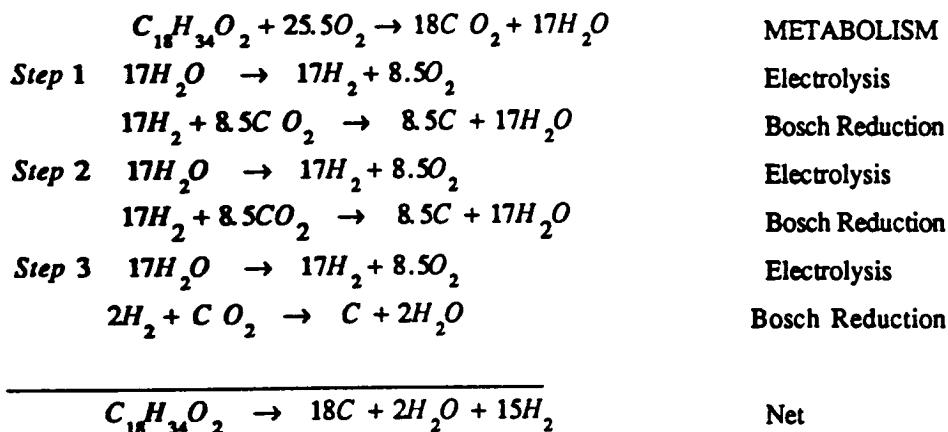


In the Sabatier reactor, the products are methane and water

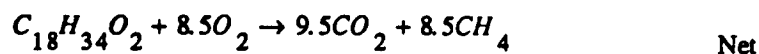
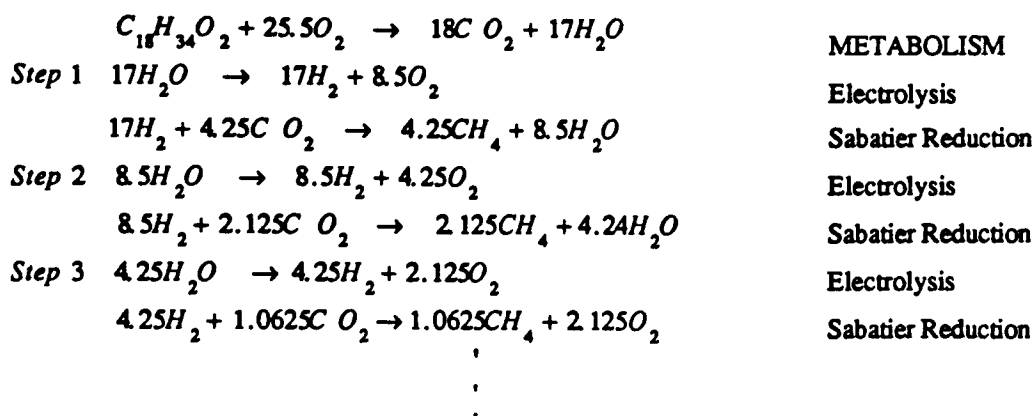


The Sabatier reactor has the advantage that the catalyst is not contaminated with the carbon deposits which occur in the Bosch reactor and a much higher single pass conversion rate. Unfortunately, the Sabatier reactor will not close the oxygen supply if there is metabolism of reduced foods or combustion of reduced trash.

To illustrate the lack of closure with the Sabatier reactor, consider a diet of pure fat (the most highly reduced food). The sequence of reaction steps for the Bosch reaction system is



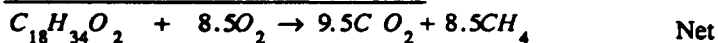
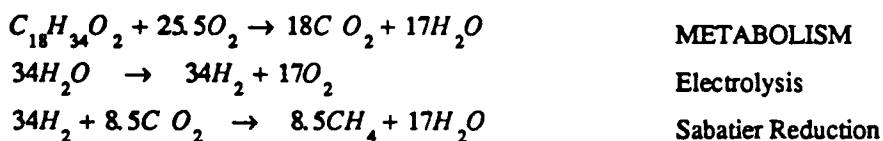
Notice that the net reaction requires no additional input of oxygen. The reaction sequence for the Sabatier reaction system is



The water coefficients (X) of the electrolysis/Sabatier reduction steps form the series

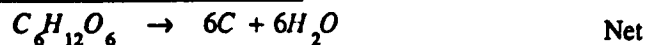
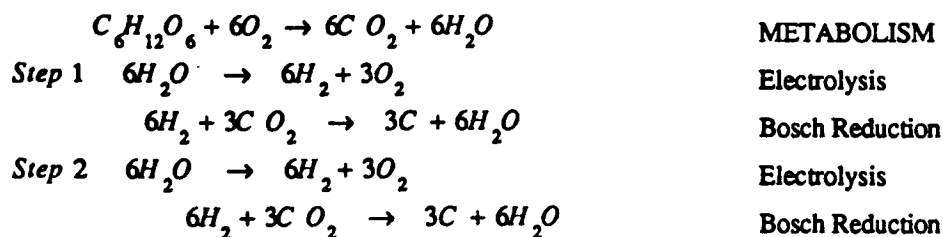
$$X + \frac{1}{2}X + \frac{1}{2} \frac{1}{2}X + \dots = \sum_{n=1}^{\infty} \frac{1}{2^{n-1}} X = 2X$$

where n is the step number. This infinite series converges to 2X so the Sabatier reaction sequence may be summarized as

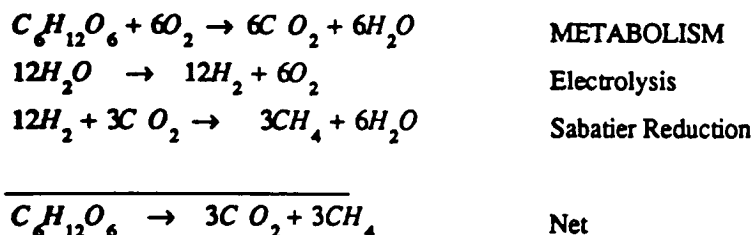


Again, notice that the net reaction requires additional oxygen input.

If the diet were solely composed of glucose, the Bosch reaction sequence is

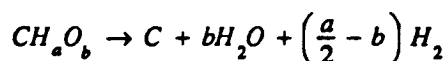


Using the summarized reaction sequence of the Sabatier reactor, the net reaction for a glucose diet is

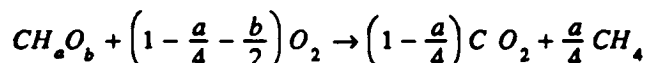


With the pure glucose diet, both the Bosch and Sabatier reactors do not require a net input of oxygen. However, since a pure glucose diet is impractical, the chemistry of the Bosch reactor is required.

The critical feature of the food which determines whether oxygen closure is possible is the C:H:O ratio. Consider the formula for generalized food; CH_aO_b . Fig. 3 shows that the generalized net equation for a Bosch reactor is

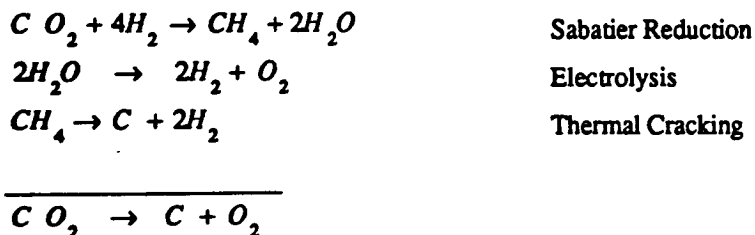


A net input of oxygen would never be required for the Bosch reactor. For the Sabatier reactor, the generalized net equation is

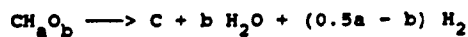
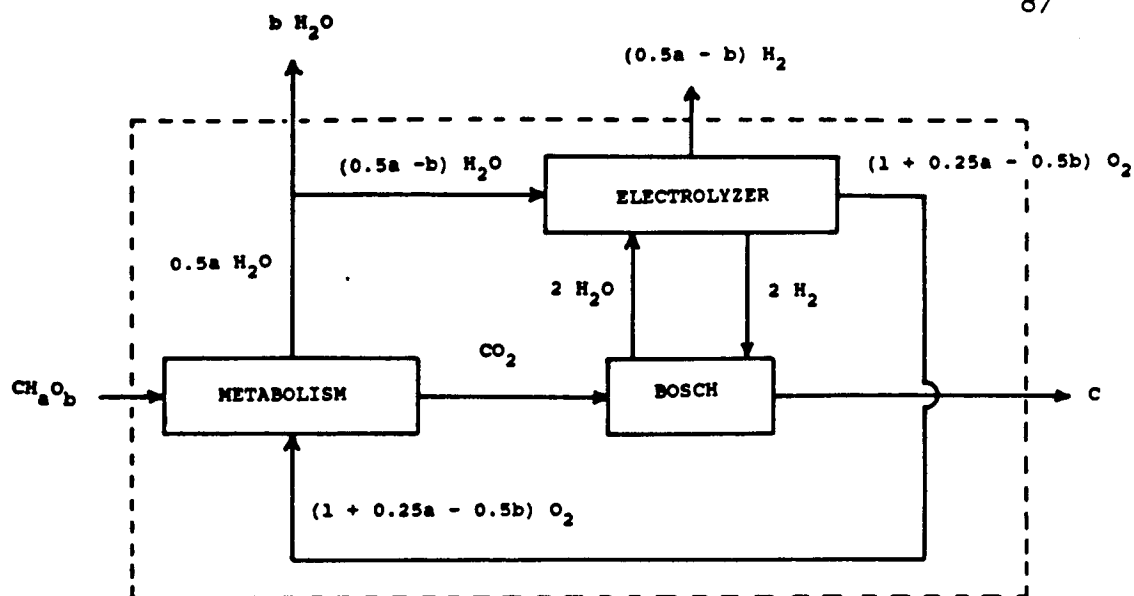


A net input of oxygen is not required only when $1 - a/4 - b/2 \leq 0$ which is the case only for monomer sugars (e.g., glucose). This condition does not hold for other foods such as starch, sucrose, fats, or proteins, so if these foods are incorporated into the diet, net oxygen input will be required.

A "pseudo-Bosch" reactor can be created by thermally cracking the methane product of the Sabatier reactor.¹⁹ The net reaction of this system is



which is identical to the Bosch chemistry. The decision to use a Bosch or "pseudo-Bosch" scheme would be based on system weight, reliability, controllability, energy usage, absence of side reactions, etc.



SABATIER

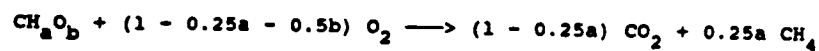
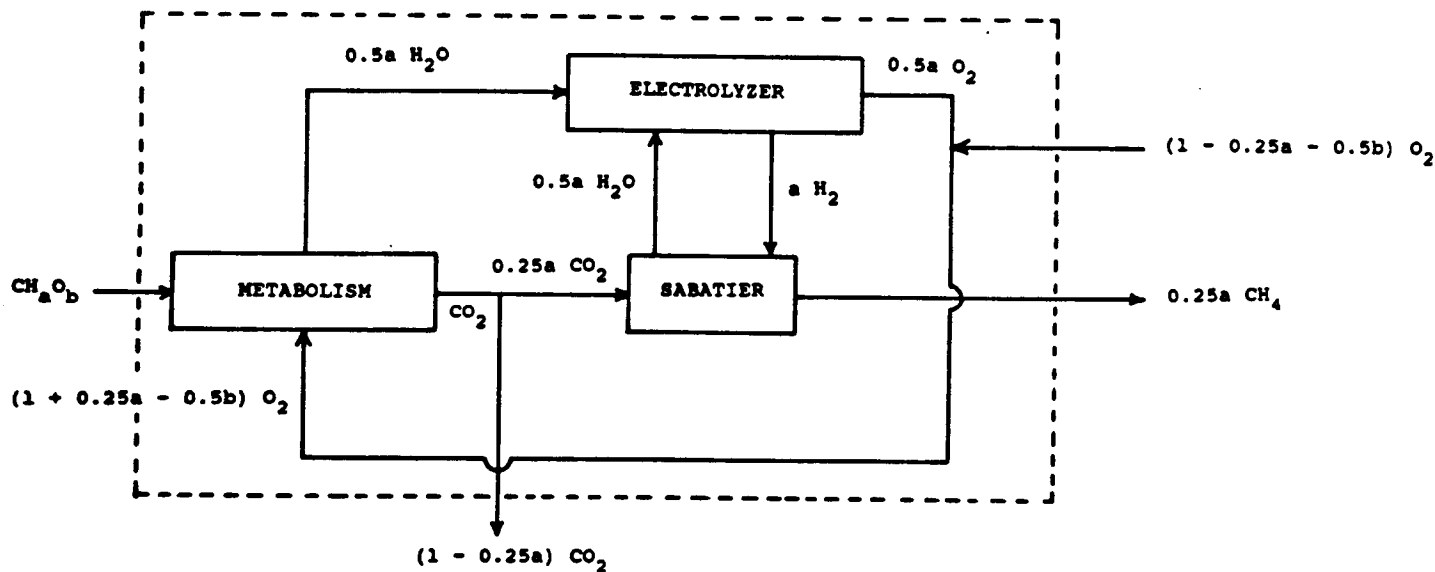


Figure 3. Flow of chemicals in the Bosch and Sabatier reaction system.

Three concepts for regenerating food have been presented; algae, higher plants, and the "artificial chloroplast." It is important to assess the degree of closure possible with each of these options. The degree of closure determines whether components will have to be brought into space or if there will be a net production of materials which may be used for space manufacturing.

In all the closure analyses which will be presented, it will be assumed that there is a four-person crew with an average metabolic load of 135.5 W per person.⁷³ Each person is assumed to dispose of 0.818 kg/d of trash.⁷⁵ The trash is assumed to be 50% paper and 50% polyethylene. It is assumed that each person drinks 1.3 kg/d of water and that each person sweats 0.918 kg/d.⁷³

The first case which will be analyzed for closure is algae. A type of algae which is suitable for human consumption is *Chlorella*. It is composed of approximately 21% digestible carbohydrate, 61% protein, 7% fat, 11% fiber on an ash-free basis.¹⁵ It is assumed to be about 90% water when harvested. Since all of the algae may be eaten, there is no "residue" as there is with higher plants. Figure 4 shows the effect of varying algae in the diet. The food depletion depends heavily on whether the supplemental food taken from food stores is fat or starch. Since fat is the most highly reduced food, it has a much higher energy density than does starch. Therefore, in order to support the metabolic activity level of the four astronauts, much less fat is required than starch. Any real diet which is used to supplement the algae would not be composed entirely of starch or fat. However, these two examples represent the two extremes since starch is the most highly oxidized food and fat is the most highly reduced food. A real diet would necessarily fall between these two extremes. Regardless of the amount of algae in the diet, there is accumulation of hydrogen. The hydrogen accumulation does not depend significantly whether the supplemental food taken from stores is starch or fat. The carbon dioxide accumulation, however, does depend strongly on whether the supplemental food is starch or fat. As more starch is included in the diet, the amount of carbon dioxide accumulation increases. This does not happen when fat is added to the diet. Because of the control strategy employed (see Appendix B), there is neither accumulation nor depletion in the oxygen and water storage tanks.

An example of a very productive plant is the Irish potato. The edible tuber is composed of 84% digestible carbohydrate, 13% protein, 0% fat, and 3% fiber.⁶⁷ It is 80% solids.⁷⁴ The inedible tops are composed of 30% carbohydrate, 19% protein, 0% fat, 45% fiber, and 6% lignin.⁶⁷ The tops are assumed to be 95% moisture. The ratio of dry inedible material to dry edible material is termed the "residue coefficient." In the case of potatoes, the residue coefficient is 0.275.⁶⁷ Figure 5 shows the results of the closure analysis for varying amounts of potato in the diet. The results are nearly identical to the algae.

A closure analysis was also prepared for starch produced by the artificial chloroplast. These results are presented in Figure 6. The data are identical to those presented for the algae and potatoes.

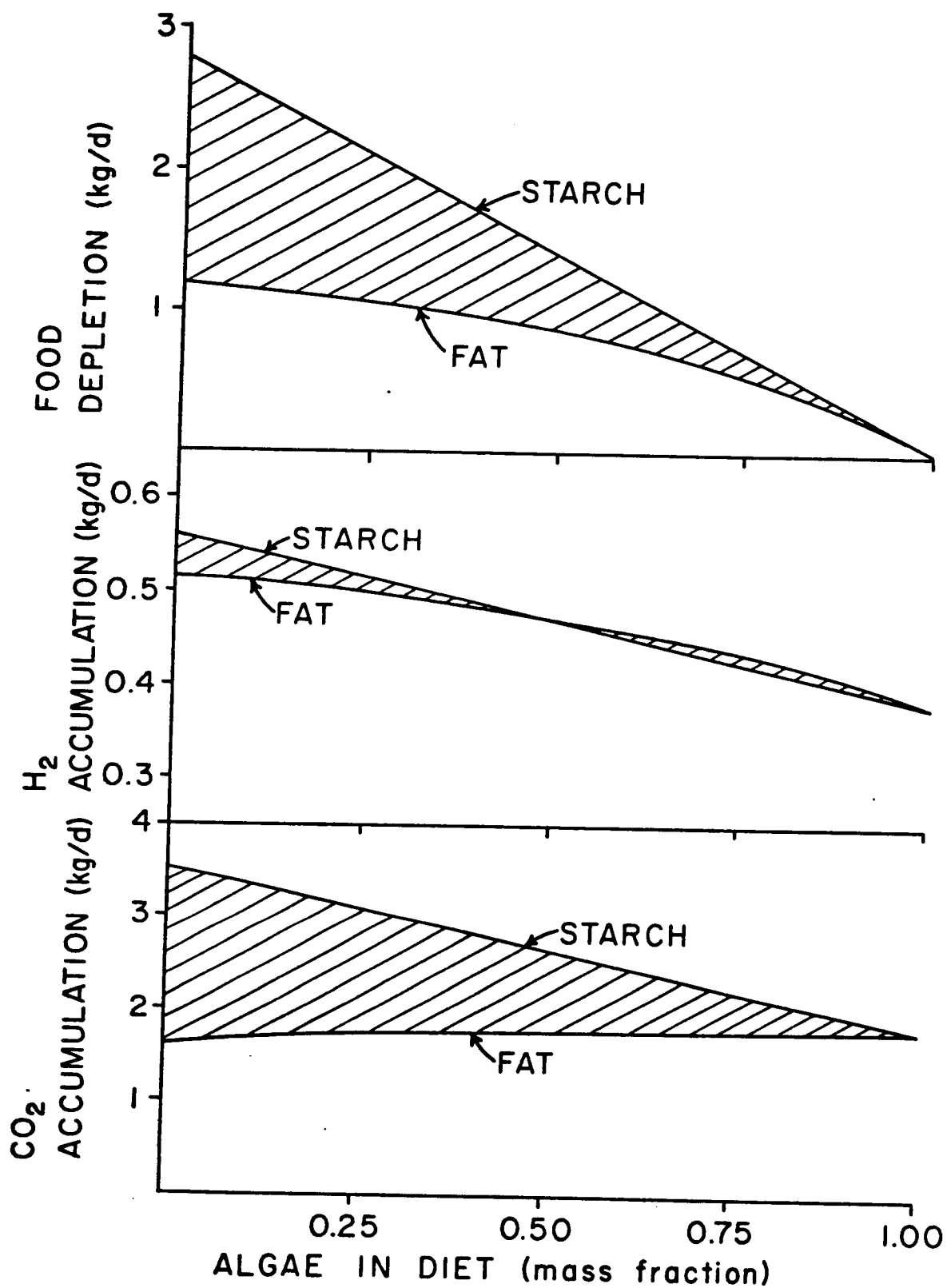


Figure 4. Closure analysis for algae.

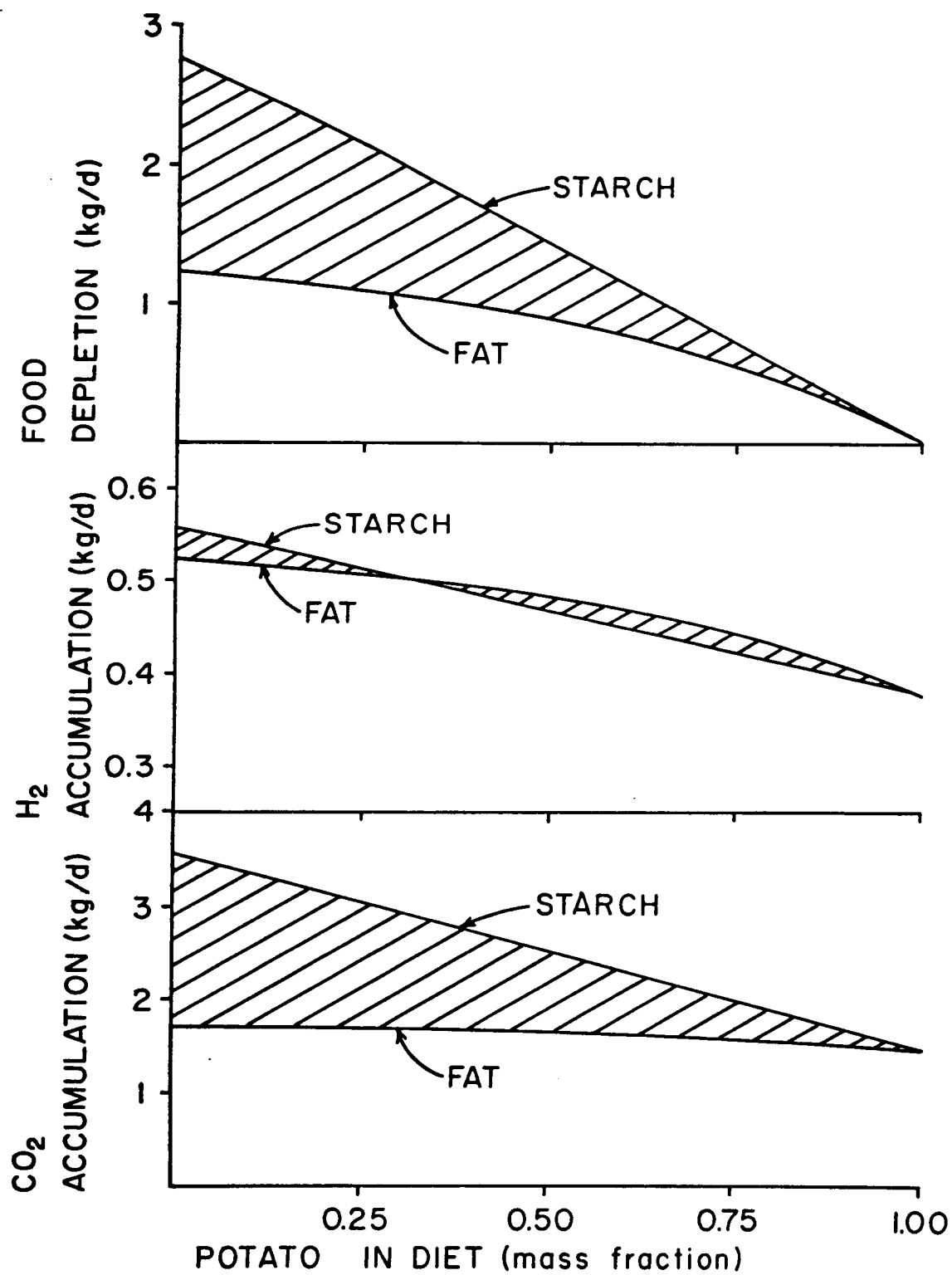


Figure 5. Closure analysis for potatoes.

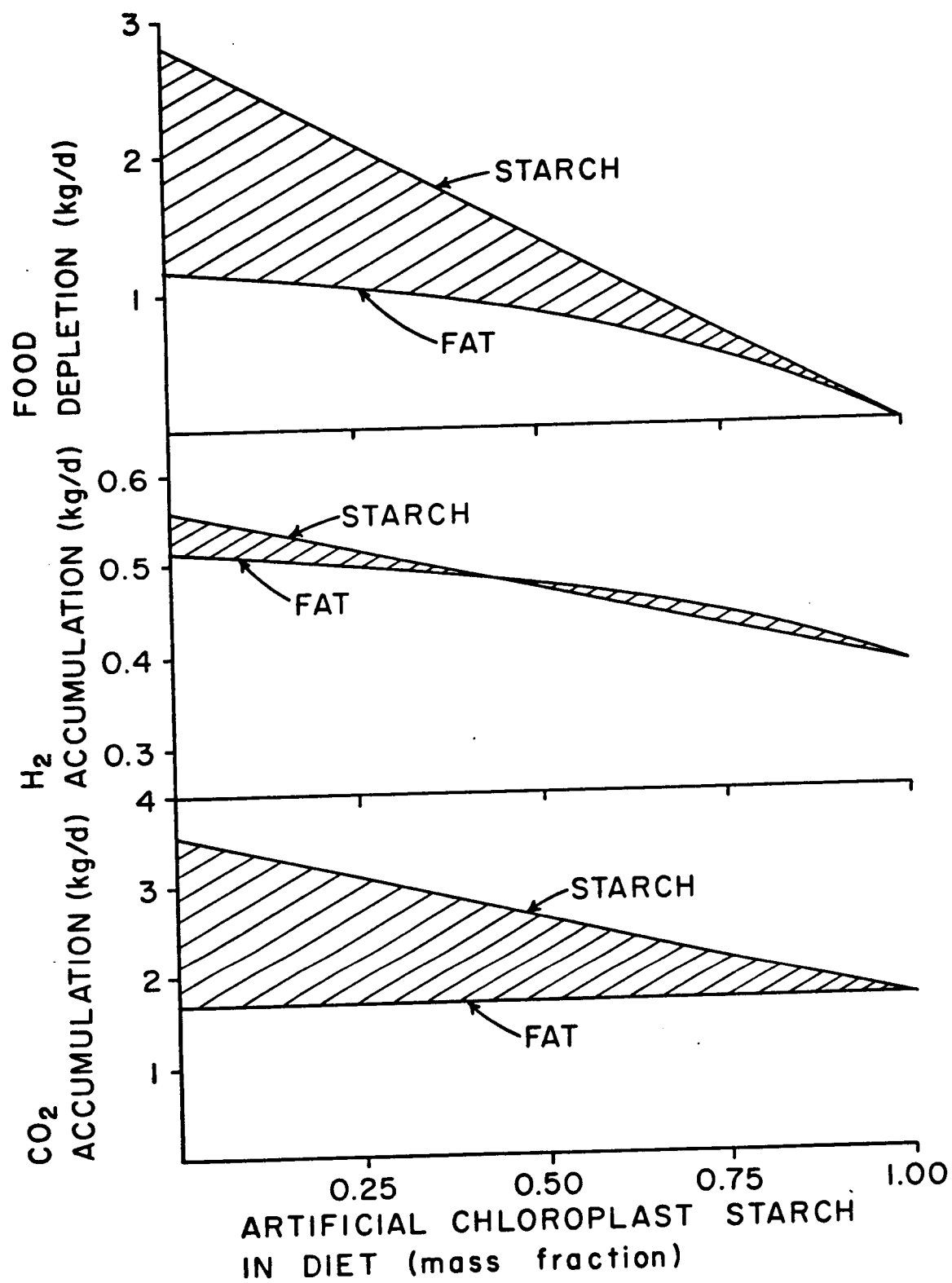


Figure 6. Closure analysis for starch produced in an artificial chloroplast.

WEIGHT ANALYSIS

Table 3 shows weight estimates for the equipment described above. The weights were assumed to scale linearly with the capacity. Although the controller and sensor weights of these pieces of equipment do not change significantly with scale, this was ignored. Since the uncertainty of the weight estimates is relatively high, the simplifying assumption that the controller and sensor weights scale linearly with capacity does not introduce significant additional error.

In performing the weight analysis, two baselines will be used. The first baseline assumes that all the drinking water, oxygen, and food are used once without recycle. All wastes are stored until ultimate disposal. This is the approach which is currently taken with the Space Shuttle. The second baseline assumes that water and oxygen are recycled but the food is not. Rather than specifying a specific diet for these base cases, bounds were provided by performing the analysis with pure starch and pure fat. (Note: both the starch and fat were bone dry.) Any real diet would have to fall between these two extremes. In comparing various food regenerating options to these baselines, it is desired to determine the "break even time." The break even time is the mission length where an equal amount of weight would have to be lifted into space for the baseline and the option being considered. For mission longer than the break even time, less weight would need to be lifted if the food generating option were used. For shorter missions, the food regenerating option does not pay; that is, less weight would have to be lifted into space if recycling were not employed.

Figure 7 shows a weight trade-off analysis using algae as a food source. If it were possible to eat 100% algae in the diet, break-even occurs in one year for Baseline 1. However, in the case of Baseline 2 where some recycle is employed, break-even occurs between 2 and 4 years depending on the food being supplied to the astronauts. If the food is highly oxidized (like starch), break-even occurs in about 2 years. Whereas if the food is highly reduced (like fat), break-even occurs in about 4 years. Since it is not possible to have a diet of 100% algae without significant processing to remove nucleic acids, a diet of 50% algae was considered. In this case, break-even for Baseline 1 occurs in about 1.2 years. Break-even for Baseline 2 occurs in 2-5 years depending on the food being supplied to the astronauts.

Figure 8 shows the weight trade-off analysis for potatoes. Because a reactor which can produce potatoes is much heavier than an algal reactor, it takes much longer to break-even. For Baseline 1, break-even occurs in about 5.5 years. For Baseline 2, break-even occurs in about 22.8-51.2 years. Having 50% of the diet supplied by potatoes reduces the break-even time to 2.5 - 3.5 years in the case of Baseline 1 and 9.9-52.8 years in the case of Baseline 2.

Since it is not possible to supply all of the diet with algae and potato production has a big weight penalty, it is logical to combine these two food production options together. As much of the diet as possible would be supplied with algae with the remainder supplied by potatoes. Figure 9 shows the results of this analysis. Break-even occurs in about 3.5 years for Baseline 1 and 13.3 to 29.7 years for Baseline 2 when 50% of the diet is supplied by algae and 50% by potatoes.

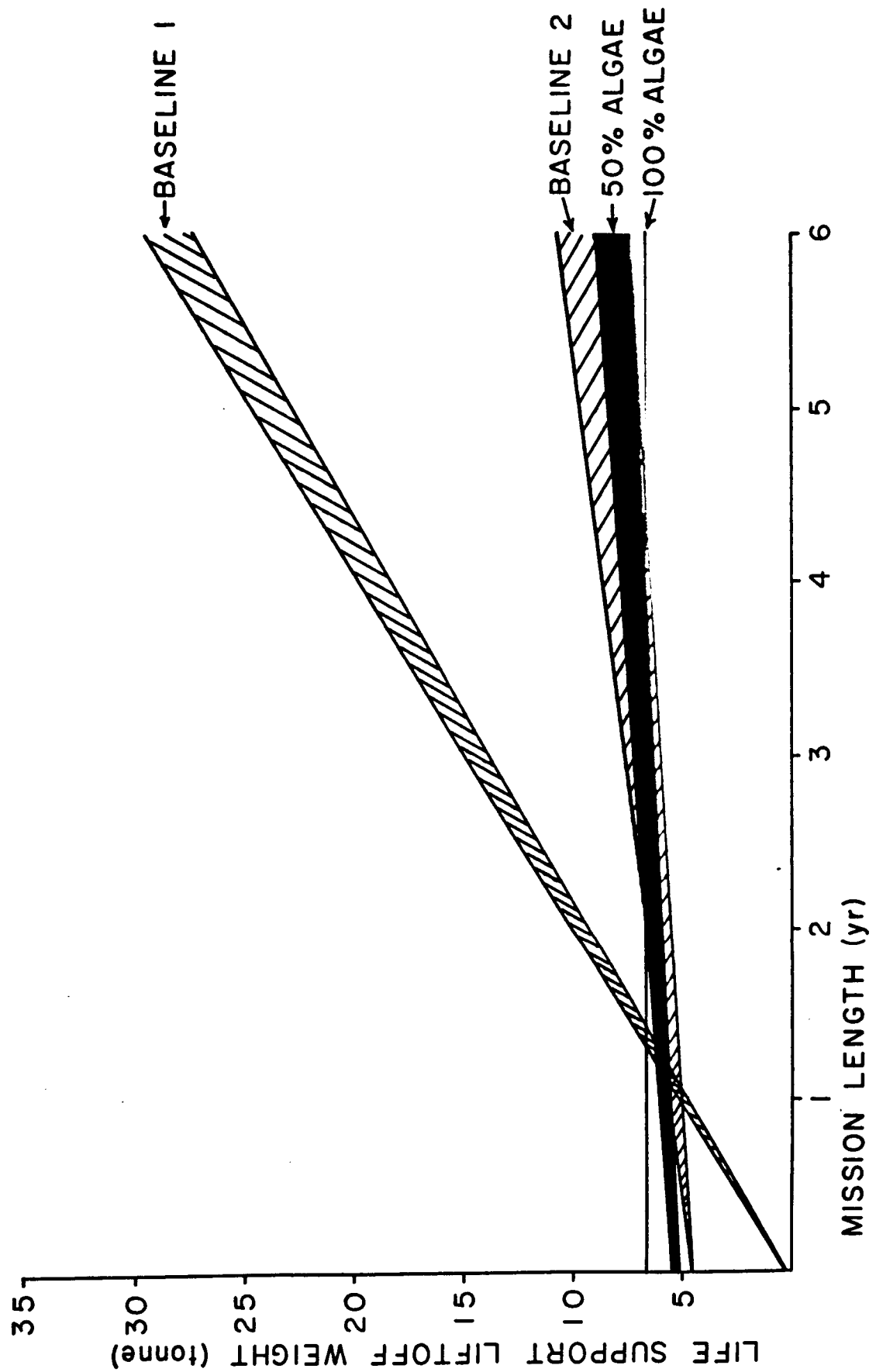


Figure 7. Weight analysis for algae reactor.

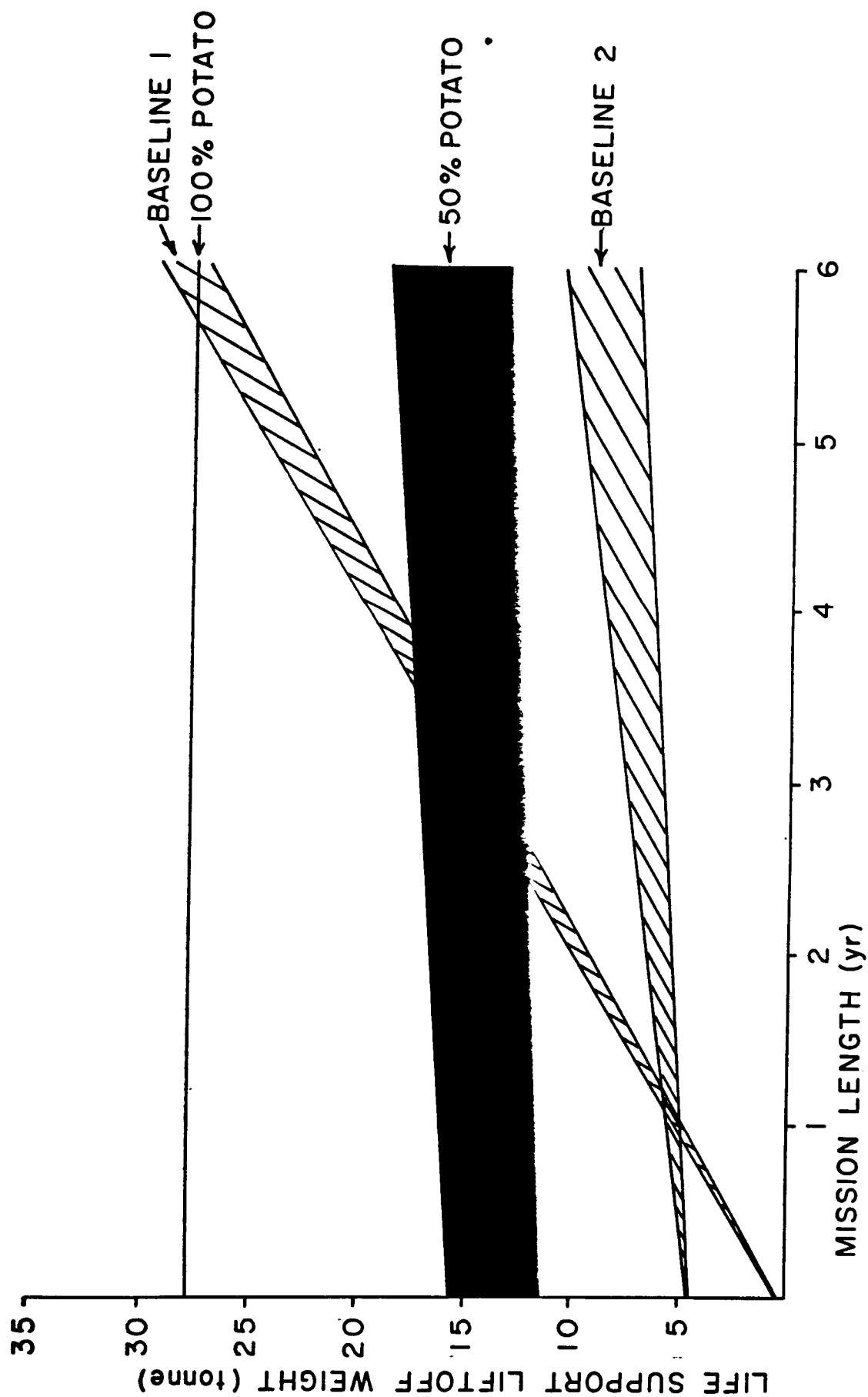


Figure 8. Weight analysis for potato.

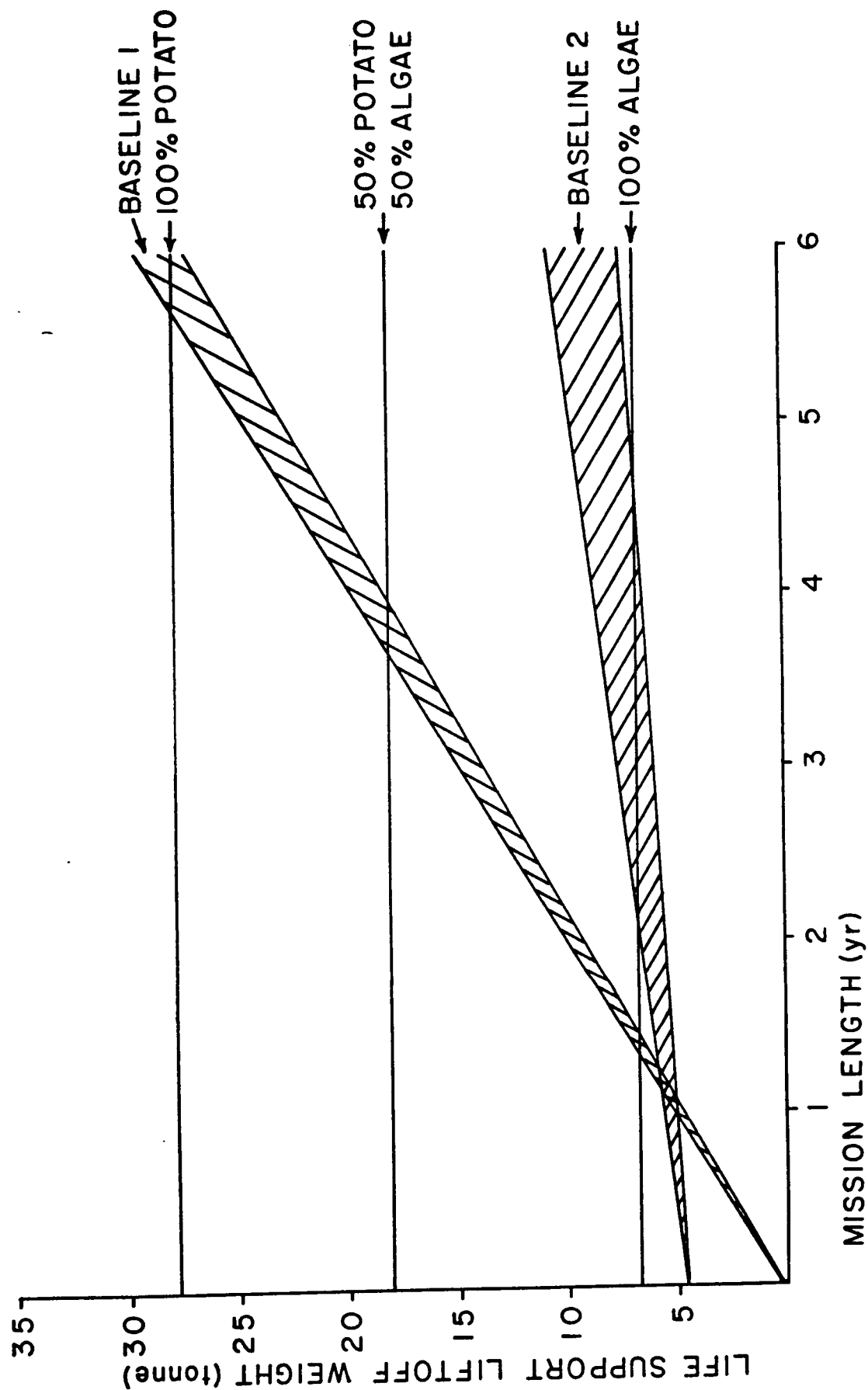


Figure 9. Weight analysis for potato and algae production.

Table 3. Weight estimates of system components.

Device		Capacity (kg/day)	Weight (kg)	Specific Weight (day)
Electrochemical Depolarizer	CO ₂ removal	6.00	265 ⁴⁰	44.2
Bosch Reactor	CO ₂ reduction	6.00	257 ⁴⁰	42.8
Dehumidifier	H ₂ O removal	11.00	46 ⁴⁰	4.2
Static Feed Generator	H ₂ O electrolysis	5.00	484.5 ⁴⁰	96.9
Nitrogen Separator/				
Ammonia Synthesizer	NH ₃ production	0.50	57.4 ⁵	114.8
RITE system	waste combustion	1.09	723.3	664
Algae Reactor	algae production	3.55	1030	290
Plant Reactor	potato production	1.0	743	7439
Artificial Chloroplast	starch production	2.79	382 ⁷⁵	137

Figure 10 shows the weight analysis for the artificial chloroplast. It breaks even in about 1 year for Baseline 1 and in 0 years for Baseline 2. This is substantially better than the other options. In addition to the quicker break-even time, it also has orders of magnitude less power requirements. It should be noted, however, that the artificial chloroplast is years away from being deployed since the research is only in the beginning stages of development.

CONCLUSIONS

Closure of the life support gases is not possible when the Sabatier reactor is used. Oxygen, hydrogen, or water would have to be supplied. Highly reduced foods (or trash) increase the need for re-supply. The Bosch reactor is always capable of closing the life support gases. A "pseudo-Bosch" reaction system which allows closure can be devised which combines a methane cracker with the Sabatier reactor.

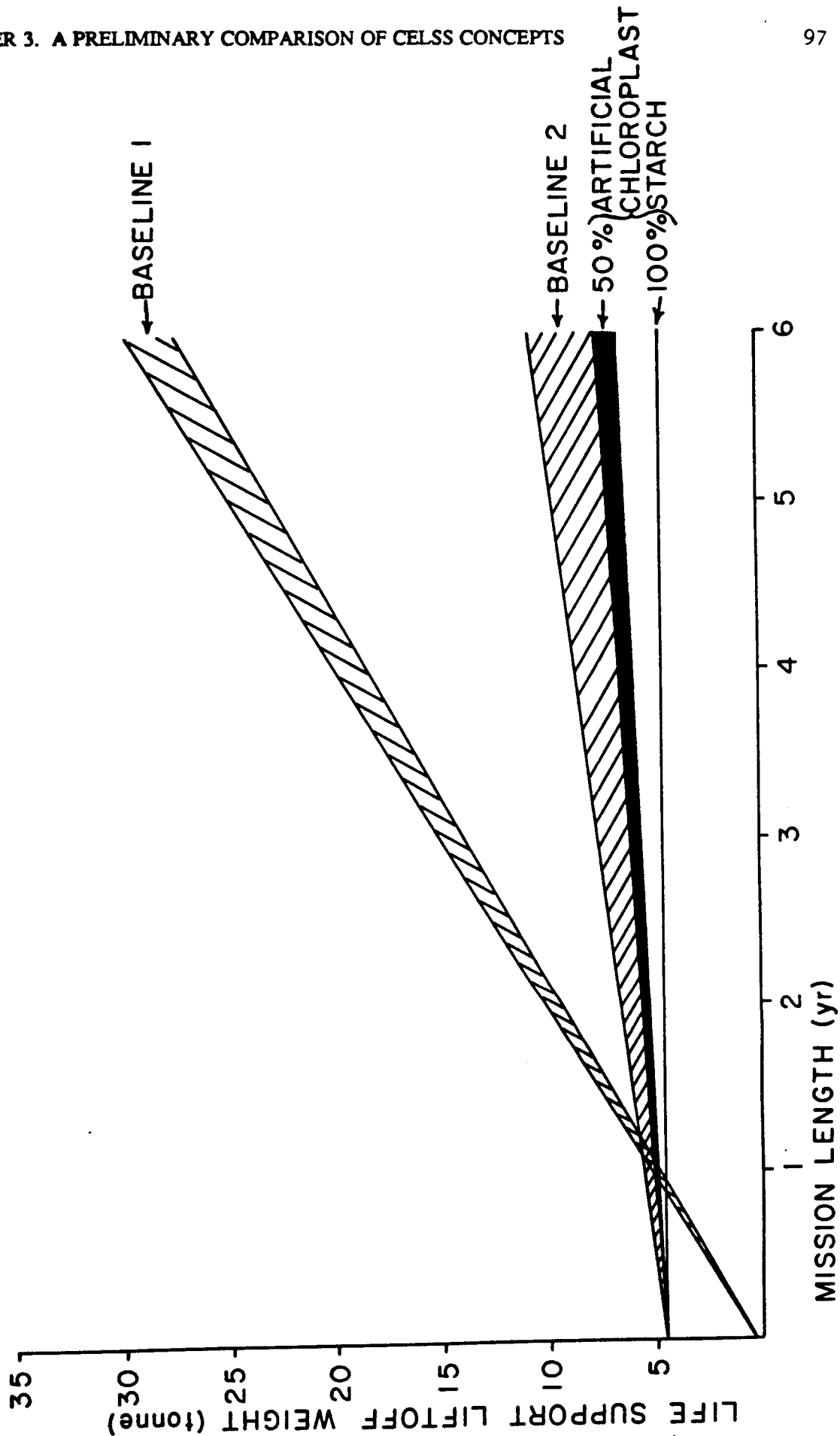


Figure 10. Weight analysis for artificial chloroplast.

The production of higher plants would provide the most palatable food for the astronauts. However, higher plants have a tremendous weight penalty associated with their growth. Perhaps innovative designs will be able to reduce the weight penalties significantly below the weight used in this analysis.

Algae can be grown in much lighter growth chambers than higher plants. However, algae cannot comprise 100% of the diet without removal of nucleic acids. Also, there are questions of whether the astronauts can tolerate the flavor and texture of algae over extended periods of time.

The starch produced by the artificial chloroplast can in principle provide 100% of the energy requirements of the astronaut. Also, the artificial chloroplast is significantly lighter than the other options and requires much less power⁷⁵. However, it is many years away from being fully developed.

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SECTION III
INTERDISCIPLINARY RESEARCH

Chapter 1
INTERDISCIPLINARY RESEARCH
LABORATORY

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Chapter 1

INTERDISCIPLINARY RESEARCH LABORATORY

The Regenerative Concepts Laboratory (RECON Lab) was established to provide an interdisciplinary facility and working environment where engineering and science researchers and students could conduct experiments pertaining to regenerative life support system technology. The laboratory is situated in the Department of Mechanical Engineering in Room L-314 of the Engineering-Physics Building. A description of the laboratory design and preliminary studies are found in our previous report.¹

During October-November 1987, laboratory facility outfitting with cabinets, sinks, water, compressed air and natural gas was completed.

A brochure describing various aspects of the laboratory purpose, nature of the interdisciplinary research team, and our approach to regenerative life support system research was prepared.

On November 13, 1987, the Regenerative Concepts Laboratory was officially dedicated in ceremonies at the Engineering-Physics Building. Guests from NASA, General Electric, University officials, Deans, faculty, staff, and students were in attendance.

During the ceremonies, officials from General Electric formally transferred the Integrated Waste Management-Water System (frequently referred to as the RITE system) to Texas A&M University and the RECON Lab.

Following the dedication, a reception was held in the RECON Laboratory where team members discussed research projects with guests and other attendees.

We are enthusiastic about the prospects for growth and development of this laboratory. A foremost purpose for the facility is to focus on interdisciplinary research and interaction of engineers and scientists. As the team progresses, the importance of, and necessity for, cross-discipline interaction to address and resolve engineering and scientific issues is as highly beneficial.

Studies on several projects are in progress in the RECON Lab and current activities are summarized as follows:

RITE System Refurbishment

The RITE system, a water and waste management system obtained from GE, is undergoing refurbishment. R.W. Murray, the GE Program Manager for development and simulation studies conducted during the early 1970's², has provided valuable assistance in removing extraneous components from the system main-frame to allow direct access to the evaporator, condenser, and high temperature thermal unit containing the incinerator and catalytic oxidizer units. He has also provided extensive "corporate memory" concerning the development, operation and simulation testing of the system.

Since much of the accessory electrical control system, auxiliary cooling, low temperature heating unit, vacuum system, etc., were not obtained with the main console, initial efforts were concentrated on assembling, connecting and instrumenting a refrigeration cooling loop to provide constant temperature to the condenser which can easily be adjusted between 50-80° F and constant temperature heating loops which can be varied from 100-125° F for the evaporator. A mechanical vacuum pump was added to provide reduced pressure of approximately 1 psia in the evaporator and condenser. At the same time, the evaporator and condenser were disassembled, cleaned, inspected, reassembled and leak- tested.

New electronic fluid level sensors were purchased and installed in the condenser and evaporator because repairs could not be made to original equipment sensors which were producing erratic level measurements. A new series of tests were conducted to calibrate the sensors and to obtain evaporation and condensation rates at approximately 1 psia (evaporator temperature at 120° F and condenser temperature being varied at 60, 70, and 80° F. Factors influencing vapor loss through the vacuum system were noted since neither the catalytic oxidizers of the high temperature heating unit or a post-condenser vacuum cold trap are not in the flow stream

The results of this test series will be reported under a separate NASA Grant (NAG9-251) "Modification and Refurbishment of the General Electric Integrated Waste and Water Management System", Dr. Hatice Cullingford (Technical Monitor), NASA/JSC/SN12..

Refurbishment has been initiated on the high temperature heating unit containing the three catalytic oxidizers which are essential to the water vapor treatment stream for producing potable water, and the solids incinerator which will be used to decompose solid organic material from the evaporator which serves as the primary waste reservoir for the processing system.

When fully complete, the RITE System will provide a mechanism with which to test the integration of the various biological subsystems with an operational physical/chemical unit. The unit will be useful immediately for processing unneeded biomass from higher-plant and/or algae growth chambers. Additional development of system capabilities could include re-utilization of waste gases in plant atmospheres or the re-use of processed or semi-processed organic components as nutrient sources in plant growth chambers.

Characteristic of the type of integration and systems evaluation possible utilizing the complete RITE System is the electro-chemical reduction of a fecal slurry to provide a nutrient solution for algae growth. The electro-chemical reduction maintains the nitrogen originally in the fecal material in the final solution in nitrate form. The resulting solution may then be fed to the algae as a nutrient/mineral solution and the remaining slurry post-processed and incinerated in the RITE System. Potential advantages of such a combination of processing techniques include:

1. Maintenance of ammonia in nitrate form rather than supplying it as ammonium
2. Reduction in the total amount of material which must be processed through the system to incineration
3. Reduction in the amount of nitrous oxides (NO_x) released during the RITE incineration process

Algae Bioreactor

Extensive characterization of algae through physiological, biochemical and growth dynamics studies have been conducted in recent years, however advances in engineering design of compact algal bioreactor systems have been lacking. Integration of an algae reactor as a potential food production capability in a regenerative life support system is in progress. An algae bioreactor (approximately 1.2 liter capacity), including fluorescent lamps, constant temperature water circulation system for the reactor water jacket, and a gas mixing and delivery system are being assembled as a pilot model in the RECON Lab³. This unit will serve as an engineering model for modification efforts designed to improve efficiency and effectiveness of various components (i.e., light delivery components, heat rejection, miniaturizing and automating the constant temperature system, and reactor vessel design).

Design and breadboard assembly of a photodetector system to measure bioreactor turbidity is nearing completion. Turbidity is equated to cell density and this data will be used to provide an auto-dilution capability for adding replacement nutrient media to the reactor as cells are harvested. Maintaining a constant density of cells can be achieved in this manner and data feedback will be correlated to determine biomass production per unit time. Growth rates can then be conveniently determined for various gas mixtures fed into the reactor as well as assessing effects of temperature and illumination variables.

Eventually, vent gases derived from the RITE system incineration/pyrolysis unit and/or the catalytic oxidizers will be integrated as a gas source for the algal bioreactor.

Higher Plant Growth Studies In Reduced Pressure Environments:

Preliminary studies have revealed that higher plants survive exposure to reduced pressure environments of approximately 10k Pa for up to one week. To better characterize plant responses, steady-state control and monitoring of growth chamber atmosphere composition and humidity is necessary. Plexiglass growth chambers capable of withstanding the reduced pressure have been fabricated and plumbed with the appropriate gas lines (CO_2 , O_2 and N_2) routed through a master control panel. These chambers

are maintained at constant temperature and lighting within a standard laboratory-type plant growth chamber⁴.

An ACRO Data Acquisition and Control System has been purchased and integrated with a laboratory computer. This system has an 8-analog output module, 8-analog input module, 16 digital in/out channels, and an 8-thermocouple module. It will be used to control mass flow of gas mixtures (CO_2 , O_2 and N_2) as well as monitoring data from the CO_2 and O_2 analyzers, humidity and pressure sensors and temperature probes in each chamber. With this control system, steady-state configurations within the chambers can be produced.

The data acquisition and control system has been initially set up as shown in Figure 1 for real-time monitoring of conditions and plant responses in the low-pressure chambers. One preliminary test has been completed and various functional problems have identified. Correction of these problems is in progress.

Labteck "Notebook" software was purchased and installed on the computer. The software will provide system control capabilities including real-time graphics. This data acquisition system can be expanded by addition of other specific types of modules and will serve as the primary data system for other hardware component monitoring purposes. Procedures are also being established for analyzing the data after it has been collected. Various techniques are being assessed by using spread-sheet routines available through LOTUS 1-2-3 and QUATTRO software. Detailed results of this work will be reported under another NASA Grant (NAG 9-192) "Plant Growth Under Low Atmospheric Pressure", Don Henninger (Technical Monitor) NASA/JSC/SN12.

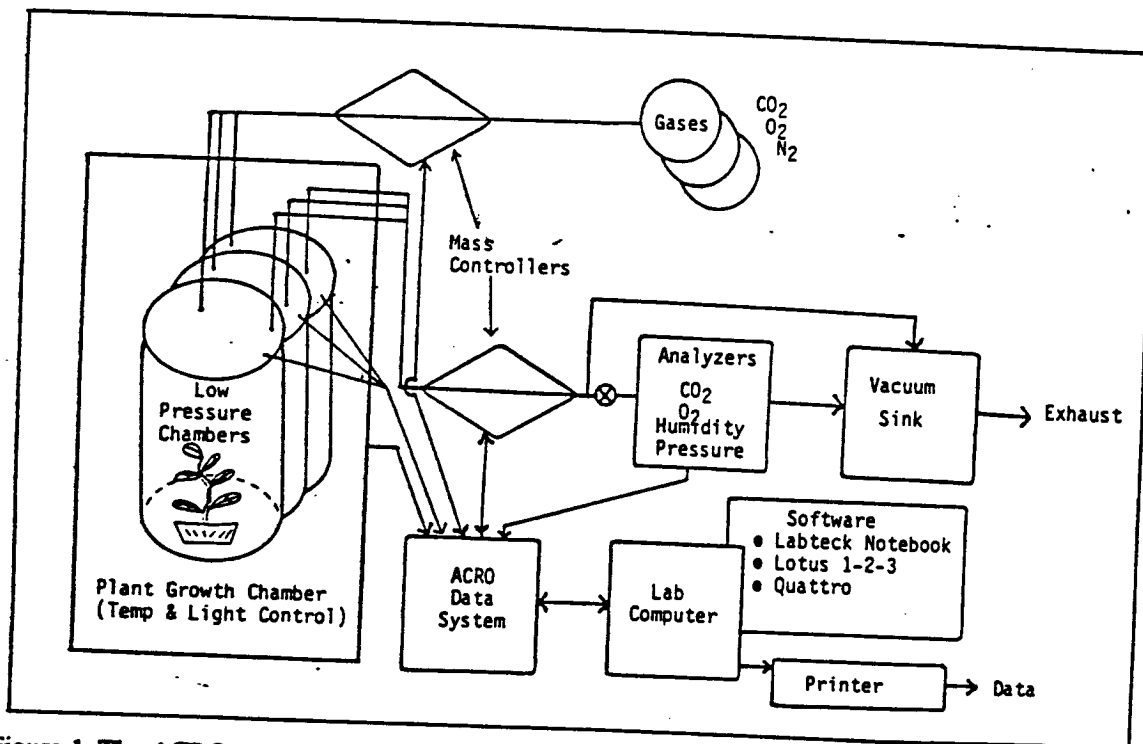


Figure 1. The ACRO Data Acquisition and control system has been integrated with a lab computer and the low pressure plant growth chambers to perform instrument control functions and data collection during test studies. This system can be expanded by addition of modules to perform other tasks for this study as well as other lab projects.

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 2

THE DESIGN OF WASTE TREATMENT TECHNOLOGY SUITABLE FOR A SPACE- FLIGHT FOOD REGENERATION MODULE

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Chapter 2

THE DESIGN OF WASTE TREATMENT TECHNOLOGY SUITABLE FOR A SPACE-FLIGHT FOOD REGENERATION MODULE

Technical Requirements of Waste Treatment Processes for Bioregenerative Food Production

Research strategies leading to waste treatment technology for life support systems are important. Water reclamation and air revitalization systems are at a more advanced stage of development (see e.g., 1,2,3) and will not be the main focus of this section of the report; however, some concepts for the evolutionary design of solid waste management systems and integration with other components of a closed loop system will be given.

The need for specific waste treatment processes arises because food regeneration systems (e.g., higher plants) cannot directly obtain significant amounts of nutrients from the types of organic waste materials (e.g., urine and feces) that will accumulate on a space mission (see e.g., 4,5). Therefore, waste treatment or, more appropriately, waste "upgrading" will need to be included in the CELSS to modify waste materials to a form that can be assimilated by plants or for alternative means of producing food.

Figure 1 illustrates, very simply, some elements of a bioregenerative scheme for food production and serves to illustrate the key role that will have to be played by the waste treatment processes. The main modification that will have to be made to the solid waste will be to provide a carbon source and a nitrogen source for food production. Furthermore, since C and N atoms of the waste produced by the astronauts will be in the form of organic chemicals and polymeric material in urine and feces, the waste treatment process will need to chemically oxidize waste materials to release CO_2 as the carbon source (CO_2 is the carbon source for all photosynthetic systems but is also the carbon source for alternative food production systems, such as single cell protein) (6,7,8). Also, NO_3^- , NO_2^- , N_2 or NH_3 need to be formed from the organic waste. The exact nature of the nitrogen source will depend on the growth system being employed.

The types of experiments to be conducted in this area are interdisciplinary in nature, since these primary waste oxidation processes must meet the specific growth requirements of complex living systems. The reverse is also true, in that the food production system needs to accommodate the limitations of the waste oxidation processes. For instance, the choice of a particular plant species (or strain) may have to take

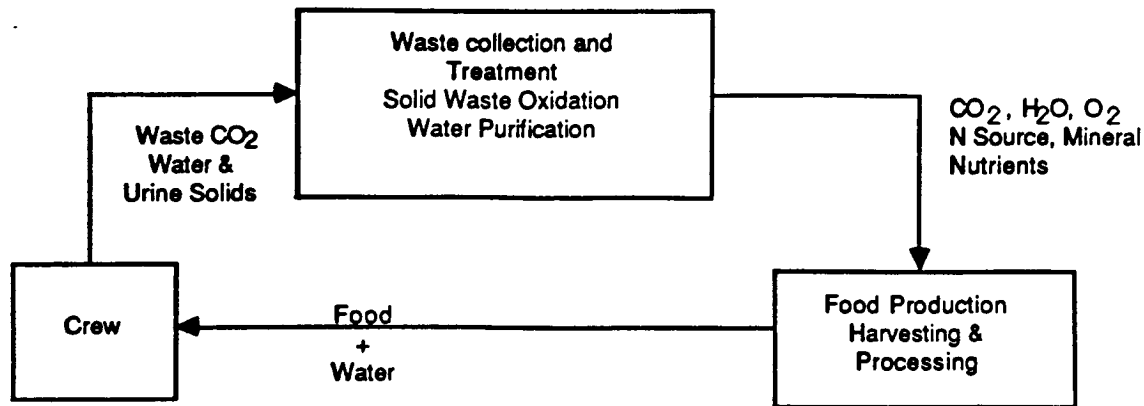


Figure 1. Component processes of a bioregenerative food production scheme.

into account how nutrients are recycled. The research approach outlined here is aimed at assessing which combinations of component systems work best with each other by combining, in a single project, the chemical science of waste oxidation with the biological science of food production to assess system development to meet stringent engineering requirements of space flight.

The experimental approach outlined has been derived partly from the assessment of waste modification procedures that were conducted in the 1960's. In particular, investigations of waste upgrading by low-temperature electro-oxidation underwent a successful phase of development at that time and has recently been revived (9,10). In preliminary assessments, this process is shown to hold good possibilities for incorporation into food regeneration schemes involving photosynthetic organisms and goes some way towards meeting the criterion laid down in Table 1. Attractive engineering features of this process include operation at cabin temperature, high degree of selectivity of nutrients, and high energy conversion efficiency.

Technical Comparisons and Assessments of Waste Processing Techniques for Bioregenerative Food Production

This section deals with how best to accomplish the oxidation of waste materials from the standpoint of both the engineering demands of the mission scenario, some of which are shown in Table 1, and the nutritional needs of the plant.

Although waste materials that will accumulate will include, for instance, plastics, food wrapping, hair and paper, for the present, the assessments given for various systems are based on the treatment of the daily organic waste products that will come from human metabolic activities.

Table 1. Desirable features of a waste processing system for bioregenerative food production.

Carbon Dioxide	Facilitate the <u>total</u> conversion of organic carbon waste to CO ₂ which is the C source of photosynthetic (and chemosynthetic) food production.
Nitrogen	Facilitate the <u>total</u> conversion of waste nitrogen containing compounds to either N ₂ , NO ₃ ⁻ , NO ₂ ⁻ , or NH ₃ as nitrogen sources for various food production systems.
Toxic Substances	Avoid the production of potential toxins (e.g., NO _x , CO, Cl ₂) during oxidation process.
Energy	Operate with minimum energy requirements.
Additional Nutrients	The oxidation process should supply all nutrients, including minerals and trace elements in a form that can be assimilated by plants easily.
Additional Processing	Single step oxidations are preferable to processes involving extra catalytic conversions.
Microgravity	Should operate in microgravity.
Adaptability	Should adapt to changes in waste composition and capacity during the mission.
Temperature	Low temperature oxidations and low pressures are desirable to minimize heat dissipation problems and simplify design.
Automation	Automated operation is desirable.

High Temperature Processes

Conventional waste oxidation processes involve high temperature combustion and will, especially since the oxidation processes are likely to be exothermic, introduce the need for adequate heat dissipation capabilities into the structure or complex heat capture and recycle. Such processes will also require the conversion of electrical energy into heat energy, a process which is intrinsically limited to around 30% efficiency (11). Conventional pyrolysis incineration, or wet oxidation, allows for little selectivity of the reaction products giving significant quantities of oxides of nitrogen and carbon monoxide which require additional (high temperature) catalytic processing.(3,5,12,13). Also, the reaction necessitates the consumption of oxygen thereby depleting on-board reserves or placing additional energy demands on the system (3) by forming more oxygen by electrolysis of water

Low Temperature Electro-oxidations

Low temperature (i.e., at around 25°C) oxidation processes that come closer to meeting the system ideals broadly outlined in Table 1, in which DC currents *are used for chemical oxidations and offer a high

*This method of waste oxidation is particularly appropriate since fuel cells and photovoltaics, are DC sources.

degree of selectivity over the reaction products and have undergone elementary but highly successful stages of development specifically for food regeneration systems (9,14,15) and currently are being investigated at the Surface Electrochemistry Laboratory at TAMU (10).

The scheme shown in figure 2a uses electrical energy and involves the electrolysis of an organic waste slurry. The reactions involve placing the waste slurry in a compartment and passing electrical current across an electrode, whereby the oxidation of waste material to CO_2 occurs at the electrode surface. In practical systems such as used in industrial situations (see e.g. 16,17), the electrode is not a flat metal sheet but consists of a bed of metallic material packed into a column through which the biomass slurry can be passed continuously. In this way, electrodes with enormous surface areas can be packed into relatively small columns for rapid processing. (18) The steady development of electrochemical technology in recent years means that advanced technology can be transferred to optimize this process. For instance, light-weight electrochemical technology associated with the development of fuel cells for the space program can be adapted for use in these systems.

Low-Temperature Waste Oxidations that Supply Electrical Energy

Figure 2b shows the principle behind a low temperature process where the waste oxidation provides electrical energy. Such devices are sometimes called biochemical or microbial fuel cells and represent an important means of waste treatment in space since they convert organic waste directly into electrical energy; however, these devices were investigated as a possible means of waste treatment for manned space missions *only for a brief period during the 1960's*. (19) Since this time, there has been a tremendous increase in research related to biofuel cells leading to great improvements in their effectiveness. (20,21).

Biochemical fuel cells utilize microorganisms to break down the large molecules that constitute organic waste. The waste is degraded (i.e., oxidized) by the microorganisms's metabolism to give intermediates that are rich in electrons. Biochemical fuel cells utilize these electron rich chemicals to create a flow of electrons.

Since the start of this decade, there has been a resurgence in interest in biofuel cells. As a result of this interest, current densities obtainable from these types of devices have improved. in the range of two orders of magnitude over those obtained during the 1960's. The improvements result from the use of redox mediators placed in the anodic compartment of the biofuel cell (Fig 2b).

Many types of organic redox mediators (i.e., low molecular weight redox couples) are able to penetrate the cell wall and cytoplasmic membrane of microorganisms. These mediators scavenge electrons from inside the cells and diffuse out of the cell in the reduced state to the anode (i.e., electron sink) where they are oxidized to produce an electrical current. From there the electrons pass through a circuit where they combine with a suitable electron acceptor (usually oxygen) at the cathode (see Fig 2b). The currents produced in the absence of redox mediators are very small.

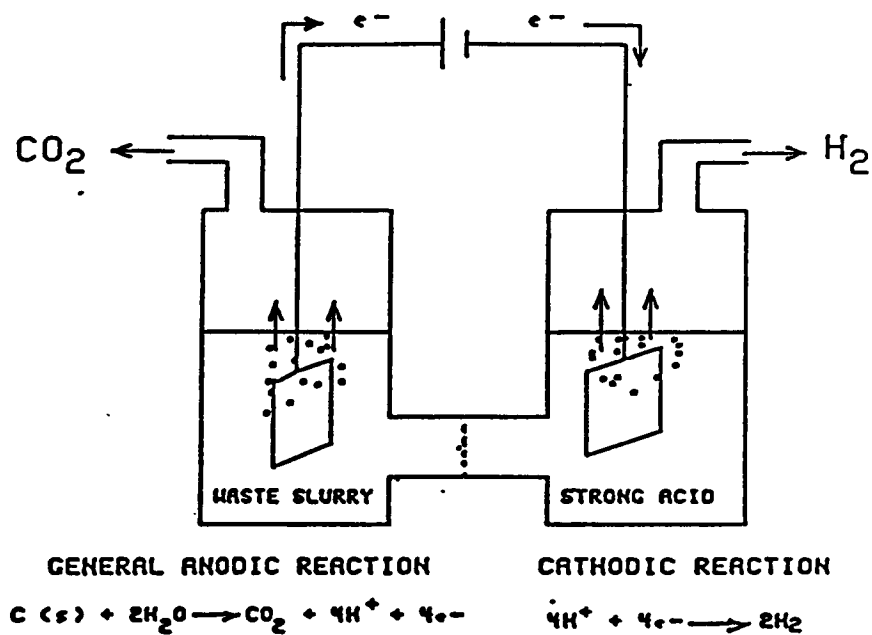


Figure 2a. A schematic representation of the method used for the electrochemical degradation of organic human wastes.

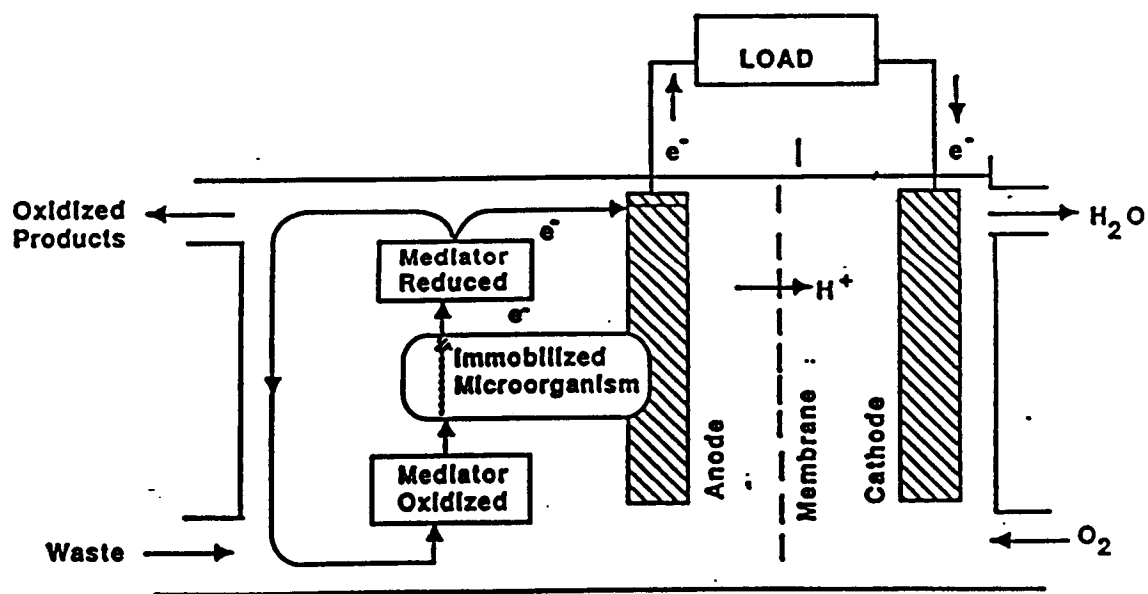


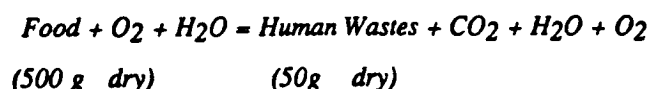
Figure 2b. Schematic of a biofuel cell with immobilized microorganisms.

All natural and most synthetic organic chemicals are susceptible to microbial degradation. Thus, by selecting appropriate microorganisms all human and organic waste can be treated in biofuel cells. Furthermore, the use of genetically engineered strains of bacteria can enhanced degradation. Biofuel cells can be constructed to generate electricity with near to 100% coulombic efficiency, therefore, the complete oxidation of organic materials is a realistic possibility (22). Selectivity is an important feature of these systems since microbial enzymes can completely oxidize waste products to give a small number of products that can be recycled (i.e., few side reactions). For example, the anticipated waste products from a biofuel cell for urine degradation are CO_2 and NH_3 which are chemicals that can be recycled. Maintaining the long-term stability of biocatalysts is a major objective of research in this area; however, microorganisms when suitably immobilized, in prototype biofuel cells for the treatment of factory effluent, can retain their oxidative capabilities for many months (22). In addition, hardware for the growth and maintenance of bacterial cultures *will not be necessary*.

Enabling technology for systems for the treatment of urine mixtures has reached advanced stages of development (24); however, more complex mixtures of organic wastes require further research. It seems likely increasing pollution controls and the need for on-site disposal of industrial/toxic waste and farm effluent may give rise to rapid advances in this area with many potential commercial spin-offs (20,21).

Electro-oxidation Waste Treatment Integration with Bioregenerative Food Production Systems: Phase 1 (Tischer, *et al.*, 1962-1965)

These workers performed a number of studies in which methods for the modification of human waste were investigated as a means of maximum recovery of nutritive material for plant growth (9,14,15) and the research centered around converting urine and fecal waste slurries into CO_2 and a nitrogen source for the growth of plants as shown below (9).



These workers maintained that if available wastes can be converted efficiently into inorganic salts CO_2 and NH_3 , this could be used with oxygen and light energy for the propagation of green plants.

In these experiments which are described in two papers (9,14), daily samples of fecal waste and urine were collected from volunteers, homogenized and stored frozen. In these first experiments, 70 ml of this mixture was placed in a glass reaction cell containing two Pt electrodes of area 100 cm^2 . In passing currents from 40 mA upwards at a cell voltage of 3 V upwards, the amount of solids in the suspension could be reduced from an original Carbon Oxygen Demand (COD) of 13.00g per liter to .74g per liter (i.e.,

a reduction of 95%) within 24 hours. Furthermore, after such an electrolysis, the solution was decolorized and became clear and did not have an unpleasant odor. Little information of the reaction products is available from the first experiments although CO_2 and NH_3 were detected. After this treatment, the remaining electrolyte contained mostly inorganic components which was diluted 1/10 and was used as a growth medium for *Chlamydomonas*; growth yields on this solution (0.975g/l dry algal cells) compared well with growth yields on a conventional nutrient medium (1.11g/l dry algal cells) and in some cases exceeded growth on the conventional medium. From this initial work, the authors concluded that this approach could lead to a very effective means of propagating higher plants from the daily output of human wastes.

More details of the process and the value of this procedure for preparation of plant nutrients were obtained from later studies (14,15). The apparatus that was used is shown in Figure 3. In this case, smaller electrodes were used 1 cm^2 and a current of 60 mA at 5 V was used; longer reaction times were necessary under these conditions since the electrode area (i.e., area of the reactive surface) was reduced considerably from the initial experiments. Carbon balances were made during the electrolysis through measurements of COD and Biological Oxygen Demand (BOD), and by measuring the gases, showed that no carbon was evolved during the electrolysis except as CO_2 . There was a reduction in Total Kjeldahl Nitrogen (TKN) from 8550mg/l to 1550mg/l, but a complete nitrogen balance could not be made. However, during this period there was an increase in nitrate nitrogen from an initial value of 63mg/l to 3100mg/l. Also a small amount of nitrogen was evolved as nitrogen gas. Importantly, under the conditions used, no chlorine could be detected in the evolved gases and experiments showed that the chloride content of the solution at the end of the experiment was similar to the initial levels.

Assessment of Power Requirement

The system used to perform these experiments was crudely designed and, hence, extremely energy wasteful. Firstly, because of the resistance in the solution between the two electrodes, large amounts of energy would have been dissipated; secondly, Pt electrodes are extremely effective at evolving oxygen (i.e., has a low overpotential for oxygen), therefore, at the high overpotentials used in these experiments, much of the current would have been used up in production of oxygen from the water present in the slurry rather than the desired oxidation of the organic material present. These problems can routinely be overcome by: (a) appropriate design of the reaction cell, (b) appropriate control and selection of the reaction potential, and, (c) the choice of an appropriate electrode material.

These points were not taken into account by these authors and no attempts were taken to introduce even simple precautions to avoid these problems. Power assessment should be made taking these factors into account. It is clear that the current used in these experiments, 0.06 A, is far in excess and a more realistic current of 0.025 A will be used below to reassess the power requirements. Also the cell voltage used in these experiments, 6.0 V, is excessive and the same results can be achieved with 2.0 V.

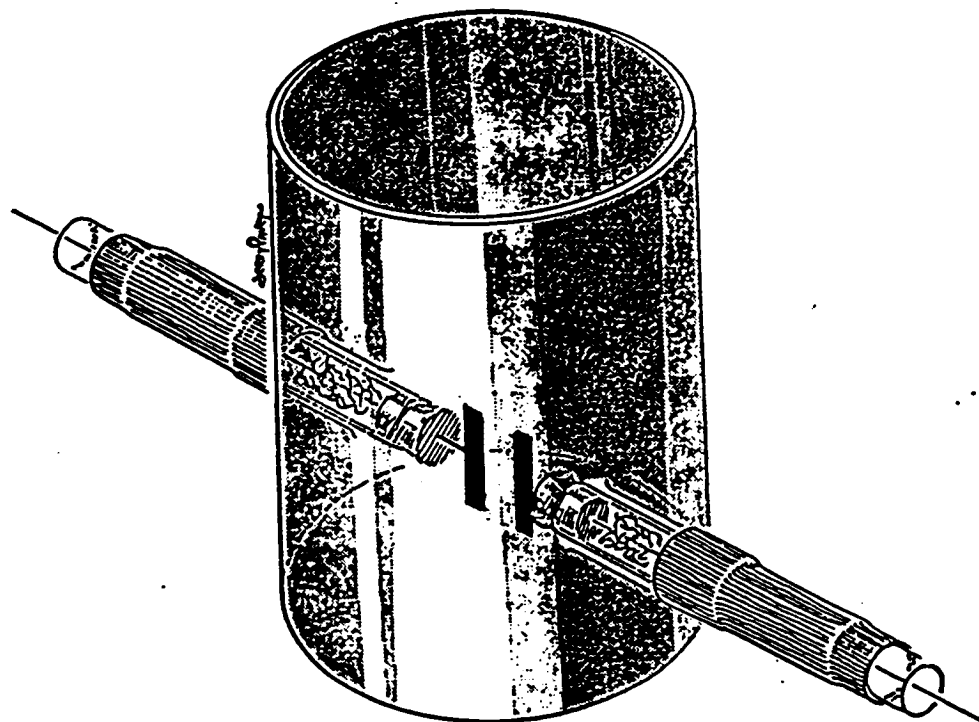


Figure 3. Electrolysis apparatus used by R.G. Tischer, *et al.* (*Dev. Ind. Microbiol.* 6, 1965, 239).

The volume of the vessel was 100 ml. Pt electrodes 1 inch² were used and mounted allowing removal and weight determinations during the electrolysis.

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Assuming all other conditions are the same as those used by Tischer, *et al.*, then the power required to convert 10 ml of concentrated waste will be 0.025 A multiplied by 2.0 V which equals 0.005 watts/ml. Therefore, to obtain almost complete electrolysis of the daily waste output of one man for one day (1600ml), the power required would be

$$0.005 \times 1600 \times 48 \text{ hours} = 384 \text{ watt hours or } 0.384 \text{ kwatt hours.}$$

Electro-oxidation Waste Treatment Integration with Bioregenerative Food Production Systems: Phase 2 (Bockris, *et al*, 1986-present)

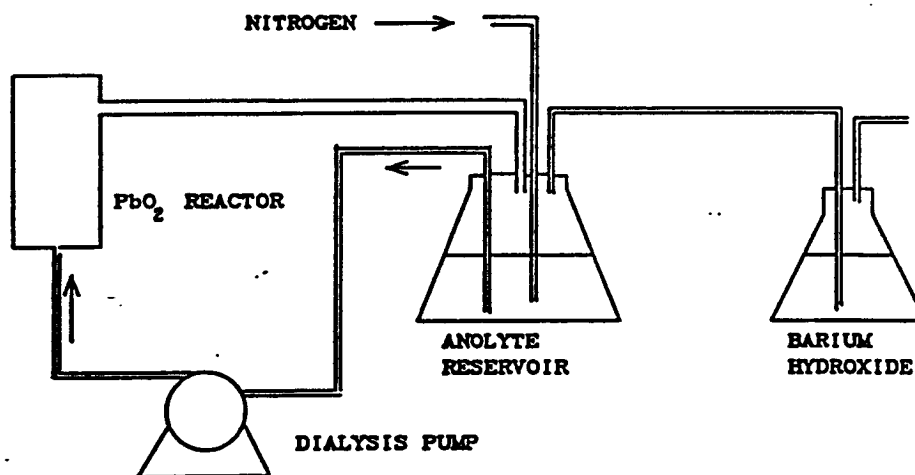
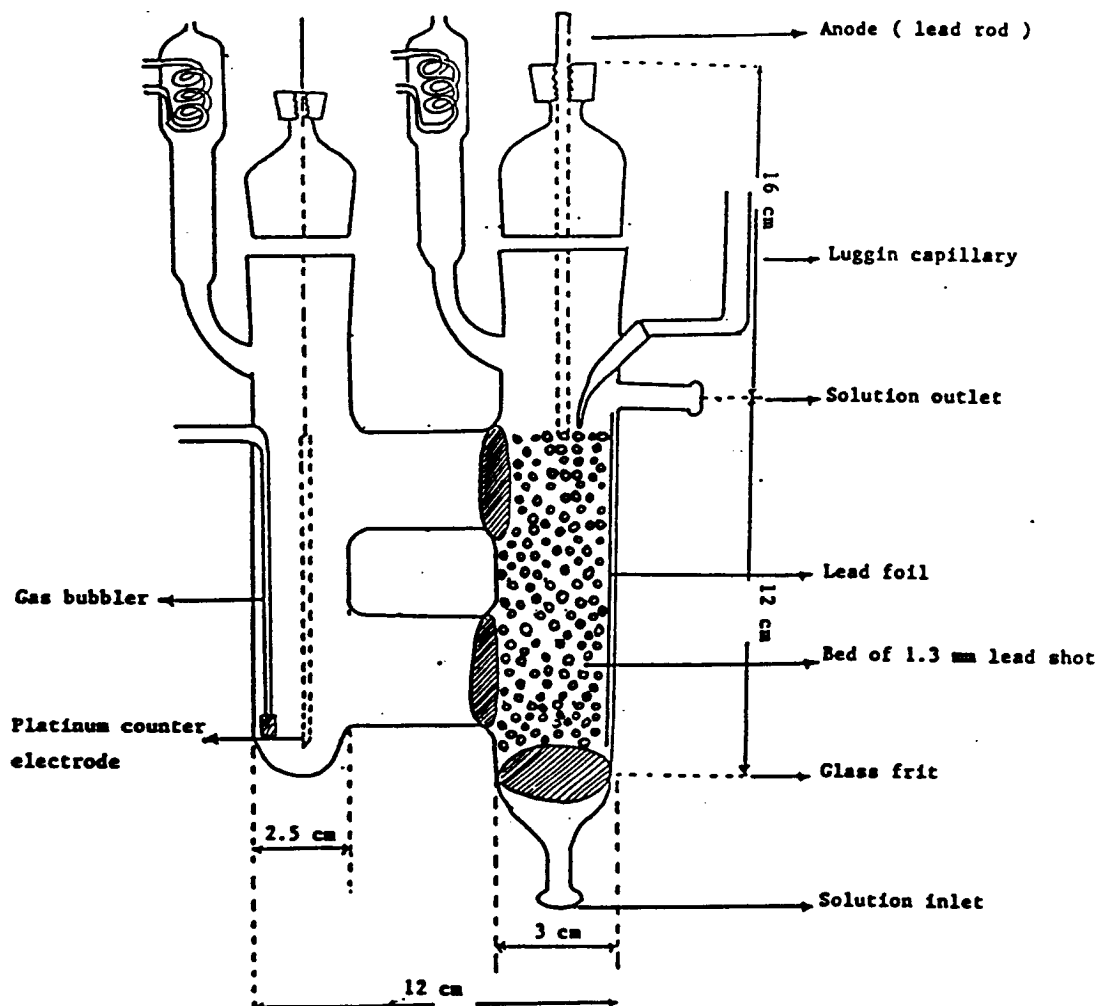
This work was initiated in collaboration with the Crew & Thermal Systems Division of JSC in Houston, Texas with the objective of developing an advanced electrolysis system for solid waste management and disposal on manned space missions (NASA Grant NAG 9-192).

Work has been undertaken to optimize the conversion of solid waste to CO₂ at low temperatures through developments in several key areas. These include: (a) determination of optimum potential range for organic waste oxidation, (b) use of bulk electrolysis techniques, (c) assessment of pretreatment procedures, and (d) selection of appropriate electrodes. Additional research areas leading to the optimization of this system have been identified and are listed in Table 2.

Table 2. Research areas leading to advanced reactions for the low-temperature electro-oxidation of organic waste slurry.

Bulk Electrolysis	Use of high electrode areas in packed-bed columns for rapid processing.
Electrolysis	Selection of electrodes with a high over-potential for oxygen evolution and are highly catalytic (i.e., have low over-potential) for organic oxidations.
Avoidance of Chlorine Evolution	Selection of appropriate potential range to minimize Cl ₂ evolution and use low-energy requiring (dimensionally stable) RuO ₂ electrodes for Cl ₂ → 2Cl ⁻ conversion.
Reactor Design	Specific design of bioreactor and placement of electrodes to minimize energy loss through cell resistance.
On-line Analysis	Examining for potentially toxic products and continuous monitoring of TOC and TKN will facilitate process regulation.
Electrode Surface Regeneration	Develop the use of interchangeable roles for working and counter electrodes. Use of intermittent voltage pulses to clean electrodes..
Reaction Conditions	Determine optimal temperatures; use of sonication, for particle breakdown during oxidation.

Bulk processing has involved the use of a packed-bed reactor and a continuous circulation system as shown in Figure 4. A key feature of the design of this reactor is that hydrogen formation (at the counter electrode) and CO₂ formation (at the working electrode) have been separated into compartments. In this



FLOW SYSTEM FOR PACKED-BED PbO₂ REACTOR

Figure 4. Packed-bed lead dioxide continuous flow electrolyzer with continuous circulation system.

way, pure hydrogen can be collected for possible use in a fuel cell; thus, much of the energy costs of the treatment can be off-set.

Electro-oxidation Waste Treatment Integration with Bioregenerative Food Production Systems: Phase 3 An Interdisciplinary Systems Design Approach

The previous sections have been concerned with the identification of technology that will facilitate the selective formation of nutrients from the daily output of human waste materials. These approaches have been aimed at the eventual integration of waste treatment procedures with the growth of higher plants as the source of food for the astronaut with the possibility that the plant growth system will involve hydroponics. This section looks at a strategy for experiments that will provide the information leading to the integration of waste upgrading processes with plant growth systems.

In the initial stages of development, model systems for hydroponic plant growth using photosynthetic microorganisms or algae offer several advantages. Algal systems have high growth rates and thus enable a large number of growth experiments to be conducted in a short period of time (15). Thus, a number of experiments to assess different electrolysis regimes, reaction conditions, effects of different electrocatalysts, can be performed using this system where each experiment takes a maximum of one or two days. Such factors as toxic effects, growth yields, growth responses and rates to changes in waste composition can be accurately assessed. The growth phase of a plant is considerably longer than for photosynthetic microorganism, thus, algae may have an important role in developing integrated waste management schemes.

Figure 5 shows the preliminary design of a laboratory test-bed system for integrating waste treatment and food growth. The waste treatment system is essentially that of Tischer (9,14) that has been described in the two previous sections. This system is attractive for its simplicity in that, (a) urine and feces can be treated in a one-step oxidations and, (b) this process has the possibility of providing carbon and nitrogen sources with a suitable mineral nutrient required for growth. Furthermore, these materials are rendered in forms that can easily be assimilated by plants with only minimal pretreatments (such as gas stream drying and pH adjustments).

Table 3 shows a plan for experiments that will enable the suitability of waste treatment regimes to be determined.

Extended research, that may be performed on this test-bed include research into growth regulation in response to waste breakdown, the development of a continuous growth system and the design of in-flight experiments.

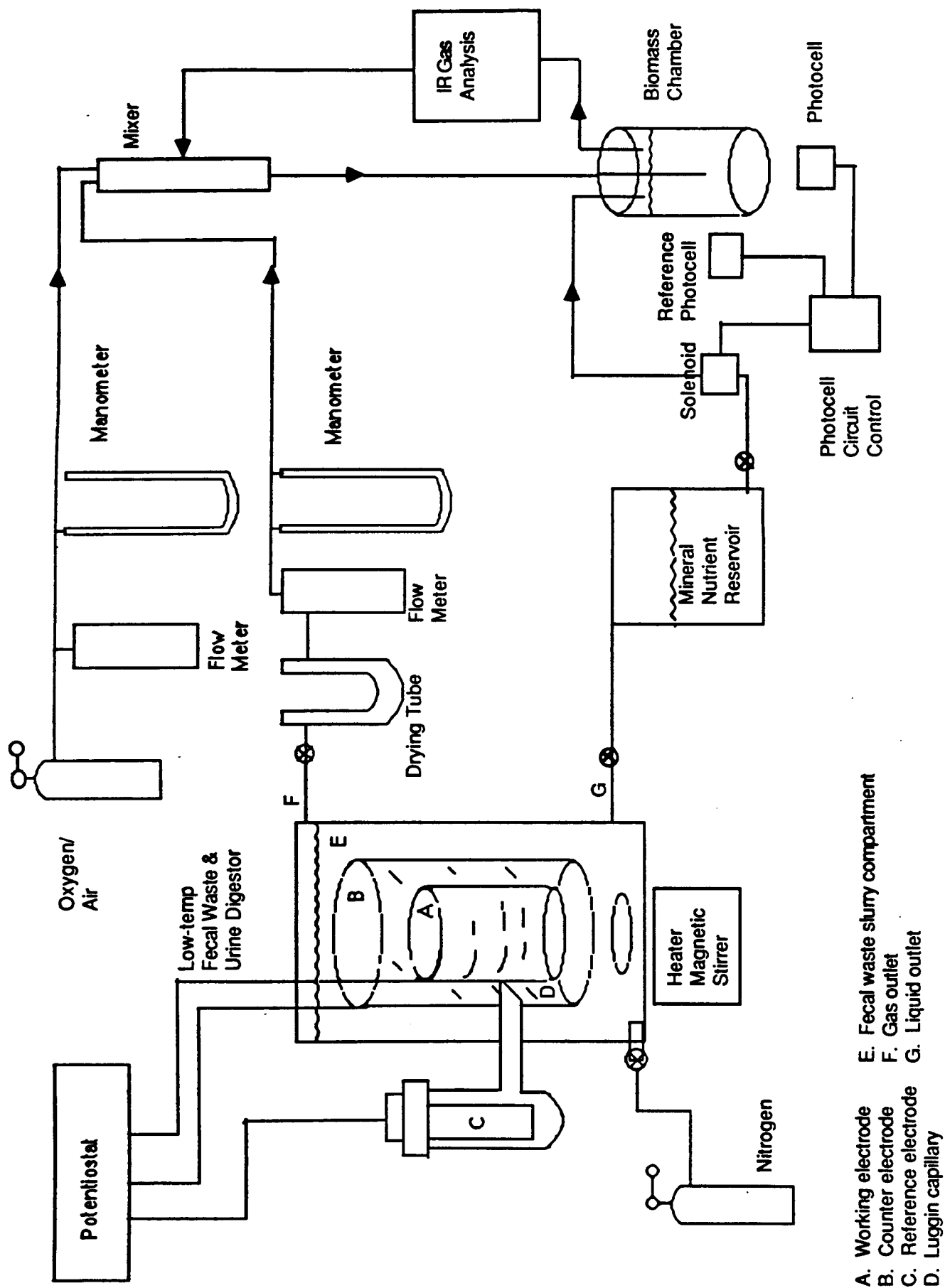


Figure 5. Management of fecal waste and urine upgrading integration with algal nutrition and gas revitalization system.

Table 3. Plant and algal growth using electro-oxidation waste "upgrading" procedures: experiments to establish nutritional value of waste treatment outputs.

Carbon and nitrogen	TOC and TKN analysis during waste electrolysis: collect CO ₂ and off-gas for growth experiments: determine NO ₃ ⁻ content of mineral solution.
Trace gas	Analyze off-gas for potentially toxic products (e.g., Cl ₂ , CO, NO _x).
Mineral Nutrient Solution	Perform nutrient analysis of mineral solution as a function of electrolysis conditions, waste composition, time of electrolysis. Determine algal growth in waste nutrient solution vs. growth on conventional nutrients.
pH	Determine factors necessary to maintain near neutral pH conditions of nutrient solution.
Subculturing	Determine the effects of repeated subculturing on algal growth.

The Evolutionary Design of Solid Waste Treatment: Solid Waste Oxidation Integration with Bosch Reactors.

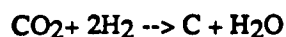
Systems aimed at air revitalization and water reclamation have undergone a considerable amount of development and will be operational in space before the implementation of food production in space. Thus, a logical step in the 'evolution' of waste treatment systems is first to integrate them with chemical recycling systems concerned with air and water reprocessing. Such an approach may serve to overcome some immediate problems of waste treatment on space stations or lunar/mars base. A scheme is proposed in Figure 6, suggests a convenient means whereby solid waste oxidation can be integrated with a Bosch reactor system which is a candidate system for air-revitalization, though a similar scheme may also involve the Sabatier reactor system (25).

The electro-oxidation system described earlier can be represented thus:



Preliminary indications are that this oxidation technique will give very little additional components such as CO (and no oxides of nitrogen) such that the gas stream from the anode will consists of CO₂ almost entirely. Hydrogen will be produced from the cathodic compartment of the reactor.

The Bosch process combines CO₂ and H₂ on an iron catalyst as follows



In operational units, CH₃ and CO are formed in side reactions (26,27). It is clear that the outputs from the waste oxidation process forms the input for a Bosch reactor and the scheme shown in Figure 6 may be suitable for development for in-flight experimentation.

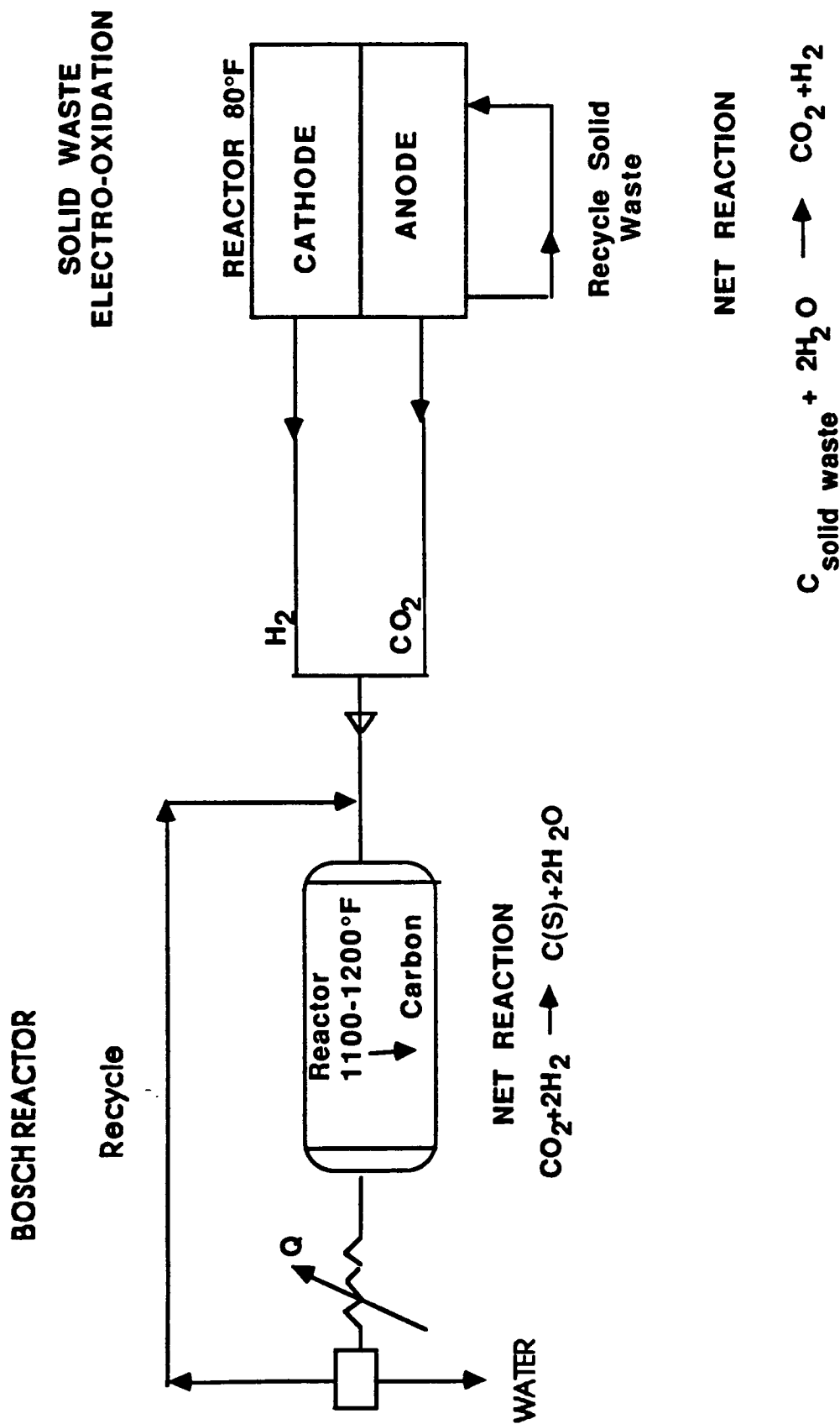


Figure 6. Solid waste electro-oxidation integrated with a Bosch reactor system.

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 3

**ADVANCES IN ALGAE GROWTH
EXPERIMENTAL APPARATUS**

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Chapter 3

ADVANCES IN ALGAE GROWTH EXPERIMENTAL APPARATUS

Biomass reactors originally appeared attractive as components of regenerative life support systems because of their gas exchange capabilities, i.e., removal of CO_2 from cabin atmosphere and replenishment of O_2 . Early studies focused on this function. All such reactors depend on the same fundamental process, namely oxygenic photosynthesis. Although photosynthesis actually consists of several dozen partial reactions occurring in sequence, it can be summarized as $n\text{H}_2\text{O} + n\text{CO}_2 + \text{energy} \rightarrow n\text{O}_2 + (\text{CH}_2\text{O})_n$, where $(\text{CH}_2\text{O})_n$ represents carbohydrate such as might be used for food. But it was recognized early on that photosynthesis and its accompanying gas exchange is accomplished only as a by-product of biomass production. That is, CO_2 removal and O_2 release are stoichiometrically coupled to accumulation of plant material. Unless these plant materials are consumed by the astronauts, they represent an ever-increasing mass of waste product which must be stored. In such a case, food stores would gradually be exchanged for stored plant biomass.

This analysis applies to any photosynthetic organism which is not completely consumed in astronaut diets, whether it be algae, higher plants, or some other organism. Higher plants such as wheat and soybeans typically produce about 40-50% of their total biomass as edible portions. White (Irish) potatoes are somewhat better in this regard, producing about 80% of their total biomass as edible material. Since processing techniques for algae are not well developed, it is not yet possible to say exactly what proportion of algal biomass may be edible, but a rough estimate puts it about 70-80%. For any photosynthetic biomass producer, only that fraction of the production which can be eaten by the crew members represents a net contribution toward closure of the system with regard to O_2 production. Material not eaten immediately becomes waste which must be stored or processed in some manner.

But even the portion of the biomass which is eaten contributes to waste accumulation. Humans constantly produce feces and urine, which contain varying amounts of organic and inorganic compounds. Unless these wastes, those derived directly from the biomass reactor and those derived indirectly after passage through the humans, can also be recycled, stored wastes will constantly accumulate. Without recycling of wastes, biomass reactors can slow, but cannot halt, the conversion of food stores into waste stores. To achieve a closed regenerative system, wastes must supply virtually all the nutrients required for

biomass growth, not only carbon, hydrogen, oxygen, and nitrogen, but phosphorus, potassium, iron, manganese, magnesium, sulfur, calcium, and 10-15 other elements as well.

One part of the RECON effort has involved examination of electrochemical oxidation of wastes. This technique appears to offer desirable features of odor removal, solids breakdown, etc. The wastes are converted to a liquid effluent, virtually odorless, bright reddish-orange in color, and strongly acidic ($\text{pH} = 2$). Although this effluent is obviously much easier to handle than the original foul-smelling mixture of solids and liquids, it still remains a waste which must be stored -- unless it can be used as a source to supply nutrients for growth of the photosynthetic biomass producers. Tests are now underway to determine the suitability of electrochemically oxidized waste effluents as nutrient source for growth of algal cells. The first step in testing the effluent was to neutralize the strongly acid material. Standard phosphate buffers were prepared to yield solutions of 0.1M and 0.05M phosphate concentrations, at $\text{pH} = 7.5$. Measured amounts of these standard stock solutions were placed in clear pyrex test tubes and measured aliquants of the effluent were added. The resulting solutions in the test tubes were sterilized in a steam autoclave, and were then inoculated with measured quantities of algal cells, taken from a healthy growing culture whose rate of growth and other characteristics were known. The alga used for these inoculations was *Nostoc macrozamia*. This organism was chosen because of its known tolerance for wide variation in nutrient concentrations, and its ability to fix atmospheric nitrogen, thus eliminating the need for added organic nitrogen supplies. These experiments are still underway, so no final results can be reported yet.

It was necessary to describe the operation of an algal biomass reactor in order to develop equations for computer simulation. The original description of the LSS referred to an algal reactor, but many of the important features are true of any biomass reactor. In order to determine the effect of the biomass reactor on the total system, we must define the rate-limiting step, or the limiting factor. This is necessary in order to be able to "turn up" or "turn down" the reactor. Suppose that you are modeling a system in which the crew size is ten. You wish to study the effect of suddenly decreasing crew size to four. Gas exchange requirements for four individuals are obviously different from those of ten individuals. What adjustments are necessary to the biomass reactor to accommodate this change? What parameter of reactor operation should be adjusted to achieve the most rapid and easily managed response?

In theory, for a biomass reactor, this could be any one of a number of nutrients, energy sources, or environmental parameters. For instance, all living organisms have an absolute requirement for phosphorus (more precisely, for the phosphate anion). If we severely limit the amount of phosphate available to the organisms in a biomass reactor, the rate of biomass production will be controlled by the rate of phosphate supply. The same argument applies to iron, magnesium, manganese, potassium, calcium, and about 10 - 15 other elements required by organisms. But controlling biomass production rates by limiting supplies of any of these nutrients does not appear to be a very satisfactory approach, for two reasons. First, many of the elements are required only in very small amounts. It would be very difficult in practice to regulate their availability precisely enough to exert the fine control we would like to have for a biomass reactor. Second,

some of these elements can be stored by organisms, or can be mobilized from older parts of the organisms to support growth in the younger parts, so fine control of the overall production rate of the reactor is again difficult to achieve. Third, response of organisms to changes in supply of these nutrients is often sluggish (response times measured in hours or days) so again, fine-tuning of the reactor is difficult.

Only four elements are required by organisms in large enough quantities, and show rapid enough reaction kinetics in their utilization, to be useful for rate-controlling purposes. These are carbon, hydrogen, oxygen, and nitrogen. For the photosynthetic organisms which would be used in a biomass reactor, carbon is invariably supplied to the organisms as carbon dioxide (CO_2); nitrogen is supplied either as the Nitrate anion (NO_3) or as the ammonium cation (NH_4); and hydrogen is usually supplied as water (H_2O). In addition to these elements, energy must be supplied as light (electromagnetic radiation of wavelength 400-700nm). In order for one requirement to be limiting, all other requirements must be supplied in excess. Since water serves not only as a nutrient source, but also as a transport fluid and suspending medium, it is difficult to restrict its availability. Although response times to changes in nitrogen availability are faster than those for iron, phosphate, and most other nutrients, these response times are still tens of minutes or a few hours, too slow for the control we want. We therefore conclude that only carbon (CO_2) and light are suitable for use as rate-limiting requirements for effective/efficient control of a biomass reactor. Which one should we use?

If we make carbon (CO_2) the limiting factor, then light must be in excess. But since the light is still absorbed by the pigments of the photosynthetic cells, the cells are receiving large quantities of energy which cannot be used for metabolism. This energy first raises the temperature of the cells, and then begins to cause photo-oxidation, resulting in destruction of the cells themselves. Providing excess light thus appears to be unsuitable for most efficient management of the biomass reactor.

What if we provide CO_2 in excess, and make light the limiting factor? This appears to have a number of advantages. First, the response times of photosynthetic organisms to changes in light intensity are very fast (milliseconds to tens of seconds). Second, if the light is delivered uniformly to the photosynthesizing tissues, there will be no danger of bleaching, photo-oxidation, or other damage to the organisms. However, there is a drawback to this approach. If light is to be limiting, then CO_2 must be provided in excess. In other words, the gas stream through the biomass reactor must always contain more CO_2 than the photosynthetic organisms can remove during the pass-through time. Therefore the exit gas stream from the biomass reactor will always contain CO_2 ; that is the biomass reactor will never completely scrub CO_2 from the gas stream. It will therefore be necessary either to provide additional physical-chemical scrubbing of the gas stream before returning it to the crew cabin, or to continually monitor the concentration of CO_2 so as to ensure the CO_2 levels are within safe limits before returning the gas to the cabin atmosphere.

In order to manage the algal biomass reactor in a light-limited mode, we must provide a system which ensures that light distribution remains uniform in spite of growth of the biomass. In a vessel

containing algae, as photosynthesis and cell growth (biomass accumulation) occur, the suspension of cells becomes more dense, or more turbid. As turbidity increases, cells at the back of the suspension, away from the light, are increasingly shaded by those cells closer to the light. Shaded cells show lowered photosynthetic and growth rates; their gas exchange is increasingly limited by lack of light energy. To achieve optimal management of the algal biomass reactor, we need to maintain the effective illumination of all cells in the culture at a constant value. This means that as cell growth (biomass accumulation) occurs, we must constantly dilute the cell suspension, so as to maintain the turbidity of the suspension at a constant value. To do this, a device is needed which constantly monitors the turbidity of the cell suspension and automatically adds aqueous culture medium to dilute the suspension when needed.

We have developed such a device; it is described below: Two Siemens model BPW21 photodiodes provide the input to the control circuit. This photodiode model was selected for its output linearity and peak wavelength of response. The two photodiodes are positioned so that one references the ambient illuminating light while the other detects the light transmitted through the growing cell suspension. The reference photodiode is mounted outside the algal reactor vessel; the measuring photodiode is mounted inside a thimble-shaped housing immersed in the algal cell suspension. The difference in outputs from the two photodiodes, adjusted for light absorption by glass and aqueous medium, will be a measure of the turbidity (optical density) of the cell suspension. This optical density thus is a measure of the cell quantity per unit volume. Cell quantity per unit volume (cell density) can then be regulated to a semiconstant value by dilution from a reservoir of aqueous medium, through a solenoid valve periodically activated by the control circuit.

The photodiodes have high output impedance, requiring the use of an instrumentation amplifier circuit (schematic in Figure 1) to determine the differential voltage between the two photodiodes. The output from this circuit is then filtered to remove harmonics of 60 Hz noise from the environment and light sources. The filter is a first order low pass with a cutoff frequency of 16 Hz. This filter also assists in negating the effects of gas bubbles in the system (the cell suspension is stirred and aerated by vigorous bubbling from an inlet tube mounted at the bottom of the vessel).

The filtered differential voltage is then sent to a summing amplifier to zero any common mode voltage differences between the two photodiodes and to zero the optical absorbance of the glass vessel and the aqueous suspending medium and diluent medium. This is a "blanking" control setting.

The zeroed output (the blank) described above is directed to a voltage comparator which can trigger an "on" state for the solenoid valve, using an external set point voltage which reflects the optical density setting chosen by the human operator. The output of the comparator will either be 0 volts for an "off" state or +5 for an "on" state.

The dilution state from the voltage comparator is sent to a monostable multivibrator which opens the solenoid valve for a predetermined time period, typically 6 seconds. The monostable vibrator is enabled by a timer which provides a 30 second time delay between solenoid openings. This time delay will ensure

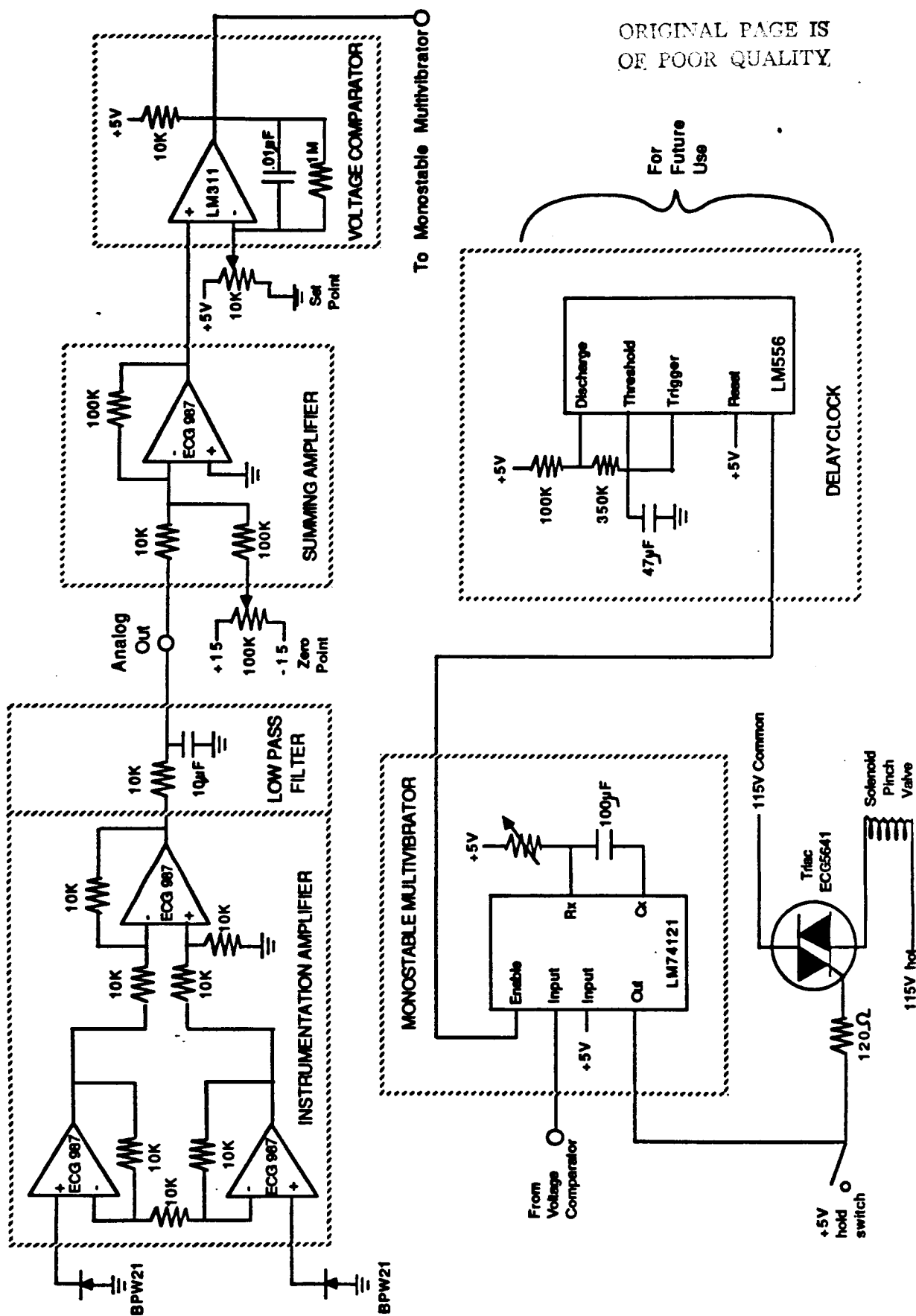


Figure 1. Schematic Diagram for Turbidity Controller for Algal Bioreactor.

that complete mixing of diluting medium with cell suspension has occurred from the previous dilution. Thus when triggered, the timer and monostable vibrator provide a maximum dilution flow rate of a 6 second pulse every 30 seconds. The circuit design allows adjustment to provide optimal control response; different flow rates. We are now testing variations in diluting flow rates to determine optimal settings for our existing reactor vessels.

The output from the vibrator is digital, and is a TTL compatible output. It is therefore possible to use the output for analysis of dilution rates, and thus of growth rates in the reactor vessels. This enables us to carry out experimental manipulations of growth conditions within the vessels, and continually monitor and analyze growth responses of the cells.

The processed digital output is directed to a triac which meets the power requirements of the solenoid valve. A bypass switch is also provided so that the solenoid can be opened on command, so as to allow repair and maintenance of the reservoir and connecting tubing.

The control system described above can be upgraded to a more continuous control system after more data have been obtained. For example, the set-point adjustment could be incorporated into the summing amplifier. The analog output of this amplifier could in turn control power circuitry which controls the position of a stepper motor. This stepper motor, via a cam assembly, would provide different levels of pressure on the connecting tubing so as to allow controlled continuous dilution flow.

SECTION III
INTERDISCIPLINARY RESEARCH

Chapter 4
ALGAL MODELS

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Chapter 4

ALGAL MODELS

ALGAL MODELS

The generalized algal model is developed from the same fundamental growth process as the higher plant models. The major difference between the algae and the higher plant model is that algae do not have a complex system of stomatal valves regulating gaseous exchange with the ambient environment. They also lack the necessity for a complex transplant and allocation system.

In addition, due to the low solubility of oxygen in water, algae do not have a photorespiration problem of the magnitude of higher plants. However, high levels of oxygen such as used by hydroponic plant growth causes algae to product glycolate which must be excreted to the surrounding nutrient solution. Higher plants recycle glycolate using the Tolbert pathway, because they do not have the option of glycolate excretion to the surrounding media.

Objective

To develop a mathematical model of algal growth which can be incorporated into a larger model, simulating the regenerative life support system. This algal growth model must be sufficiently general to account for all likely responses in space environments.

The model will be used for four purposes:

1. To provide a base for comparison of algal reactor systems with physical, chemical and other biological systems.
2. To optimize algal reactor design.
3. To manage and control an algal reactor component within a CELSS system.
4. To provide guidance in emergency procedures to ensure survival of algalculture and re-establishment of steady-state function.

Justification

An algal growth model is needed as part of the larger regenerative life support system for the following reasons:

1. Various engineering designs need to be investigated. Algae, like any organism, have internal control systems, and cannot simply be turned off and on by external valves. If such a system is to be used and controlled, the system must be designed to take advantage of all capabilities.

2. Recently, knowledge of mechanisms has increased rapidly, but information is fragmentary and should be brought together in a quantitative framework.

Approach

The algal growth model was constructed according to the integrated rate methodology (IRM) developed by Biosystems Research Group. An IRM network consists of states and transition pathways. The system under study is considered to have numerous identical individual units, which are termed system constituents. For a given steady-state period (updating time-step), the total number of system constituents is assumed to be constant. In addition, during this period, the fraction of system constituents occupying a given state i (denoted by π_i) is also unchanged. An IRM network does not have a one-to-one correspondence to the real system being studied; rather, it functionally reflects the overall dynamic behavior of the system.

For our initial formulation of the model, we have made certain assumptions. These may be listed as follows:

1. System constituents, i.e., functional units, can exist in a low-energy state (0)
2. The system constituents can be activated by light energy to go to state (1)
3. In State 1, energy can be utilized two ways:
 - (a) fixing of CO_2 , or
 - (b) formation of glycolate
4. Nutrients must be supplied; and Nutrient supply determines biomass synthesis
(Rate of biomass determined by nutrient supply)
5. Maintenance respiration is necessary and is proportional to biomass but not directly affected by light (intensity), although λ_{01} is dependent on $[\text{O}_2]$ and thus potentially on light intensity, if light intensity is below the compensation point.
6. Growth response is included in the upper cycle (in λ_{20})
7. System parameters change slowly so quasi-steady state is maintained, and therefore Mehler Reactions, Calvin cycle pool equilibration, etc. may be ignored.
8. Model is built for certain types of microalgae (namely blue-green algae, green algae, and diatoms) and is not meant to apply to brown algae, red algae, dinoflagellates, etc.

The set of π_i represents the probability of system constituents in various states i during a steady-state period. The quantitative measures of π_i s are determined by a set of external (environmental) controlling factors that influence the mean transition rates of pathways in the network. During a steady-state period, these controlling factors are also assumed to be invariants. Figure 1 shows the IRM network for the algal growth model. State 0 is considered as the regenerative state. States 1 and 2 are "energized" states, so that when system constituents return to state 0 from these states, excess energy can be deposited into external

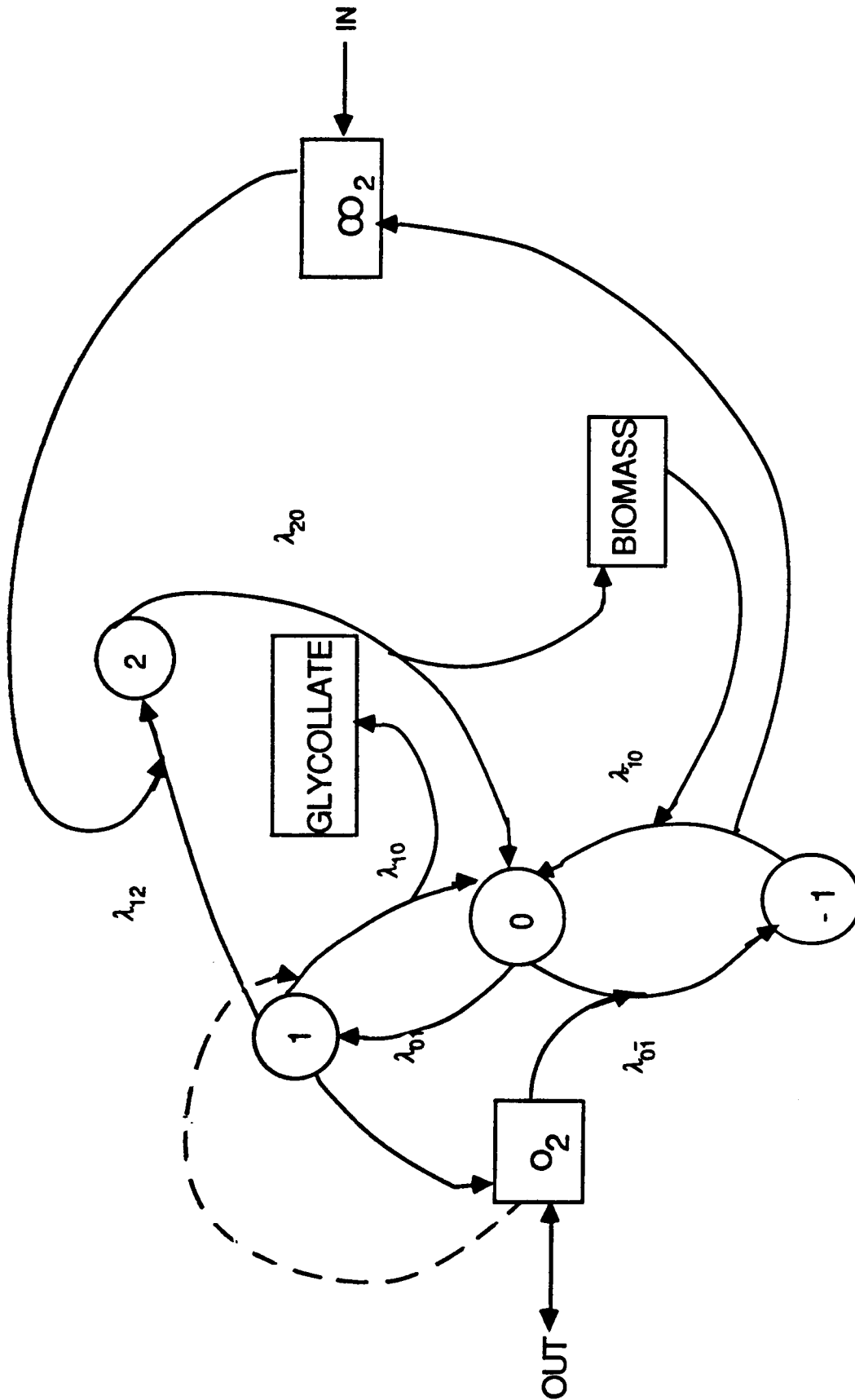


Figure 1. IRM diagram of the algal growth model. For explanation of symbols, see text.

compartmental pools (denoted by glycolate and biomass). State -1 denotes an energized state that has a negative impact on the biomass accumulation, and hence the negative state.

The mean transition rate λ_{01} between states 0 and 1 is assumed to be directly proportional to the product of light intensity L and biomass M during the steady-state period. The light intensity L can be considered as the valve of this transition pathway while the biomass M constitutes the number of functional units that are available in the entire transition network. Thus, one may write

$$\lambda_{01} = \beta_{01} M L \tau_L, \quad (1)$$

where β_{01} is the proportionality constant and τ_L is the temperature effect of effective light uptake. The temperature effect index τ_L was studied by Sharpe and DeMichele (1977) and Schoolfield et al. (1980). The range for τ is usually between zero and one. For light, however, τ_L always lies near the upper limit of one.

Other mean transition rates can be defined similarly:

$$\lambda_{10} = \beta_{10}^M [O_2] \tau_O, \quad (2)$$

$$\lambda_{12} = \beta_{12} M [CO_2] \tau_C, \quad (3)$$

$$\lambda_{20} = \beta_{20} M N \quad (4)$$

$$\lambda_{0\bar{1}} = \beta_{0\bar{1}} M [O_2] \tau_{\bar{1}}, \quad (5)$$

$$\lambda_{\bar{1}0} = \beta_{\bar{1}0} M \quad (6)$$

where $\bar{1}$ in the subscripts denotes -1 for neatness, $[O_2]$ and $[CO_2]$ refer to oxygen and carbon dioxide concentrations, respectively, and N is the available nutrient in the solution. Equation (6) deserves an explanation. The transition pathway between states -1 and 0 is fully open and not controlled by any external factor. Thus λ_{10} depends solely on the entire population of functional units during the piecewise steady-state increment

By using the equation of continuity at each state and the normalization condition for probability measures,

$$\sum_i \pi_i = 1, \quad (7)$$

the fraction of functional units occupying a state i , π_i , can be obtained. The continuity equation for state 2, for instance, can be expressed as

$$\lambda_{12}\pi_1 = \lambda_{20}\pi_2, \quad (8)$$

where $\lambda_{12}\pi_1$ represents the number of functional units transferred into state 2 per unit time while $\lambda_{20}\pi_2$ represents the emigration rate from state 2. Other equations of continuity can be established by a similar manner. Thus, there is a total of four such equations, each corresponding to a state. However, one can only use three out of four, since one of these is redundant according to a theorem in linear algebra. Coupling three continuity equations with Eq. (7), one can solve four unknowns, π_0 , π_1 , π_2 and π_3 , from four linear equations.

The compartmental pools in Figure 1 represent measurable system products. Both ambient oxygen and carbon dioxide levels can be regulated by external sources, thus the arrows in and out. The interaction between a compartmental pool and the IRM network can be categorized into two groups: (1) using the substance in the compartment as a control factor in a transition pathway, such as $[O_2]$ and $[CO_2]$, and second depositing (in both positive and negative sense) the system products into compartmental pools.

Take glycolate as an example. The increment of glycolate per unit time $\frac{dG}{dt}$ can be expressed as $\frac{dG}{dt} = \alpha_G \lambda_{10}\pi_1$, where α_G is a weighting factor that represents the amount of glycolate deposited by a functional unit. Substituting measurable quantities into λ_{10} and π_1 , Eq. (9) can be expressed in terms of L , M , N , $[O_2]$, $[CO_2]$, and τ 's.

The biomass change per unit time can likewise be obtained

$$\frac{dM}{dt} = \alpha_M^+ \lambda_{20}\pi_2 - \alpha_M^- \lambda_{10} M^x \pi_1, \quad (10)$$

where α_M^+ and α_M^- are weighting factors for depositing and depleting processes, respectively. The M appearing in the second term on the right-hand side of Eq. (10) is nonlinear because experimental evidence reveals the extraction of biomass is usually nonlinearly proportional to the existing biomass. Instead, it may be proportional to such factors as surface area of the organism. The power x , therefore, can only be determined experimentally. The change of oxygen and carbon dioxide concentration, ignoring the regulatory effects by external sources, can be written in a similar manner,

$$\frac{d[O_2]}{dt} = \alpha_0^+ \lambda_{01}\pi_0 - \alpha_0^- \lambda_{01}\pi_0 - \alpha_0^- \lambda_{10}\pi_1, \quad (11)$$

$$\frac{d[CO_2]}{dt} = a_c^+ \lambda_{10} \pi_1 - a_c^- \lambda_{12} \pi_1. \quad (12)$$

In this model, there are 14 undetermined parameters, namely six b's, seven a's and x, in addition to four temperature effect indexes, τ s all of which must be determined from experimental data. The τ s can be determined by the thermodynamic properties of the organism under study. The other parameters can be obtained by limiting some resources, for example, by letting L, N, $[O_2]$, and $[CO_2]$ approach zero one at a time. The reverse iterative approximation approach may be employed when one tries to determine parameters from system products.

Future Plans

We will continue to refine and apply the model in the following sequence:

1. We will undertake a literature search to support or refute the assumptions of the model.
2. We will also determine what processes have not been included in the model and how significant is their omission. Examples of missing processes include the Kok effect, the effect of alkaline solutions leading to excess glycolate excretion and differential temperature effects on photosynthesis, photorespiration and maintenance respiration.
3. We will construct a computer code for determining model response.
4. We will put in relative numerical values for parameters of the model and determine model responses.
5. Comparisons of model predictions with experimentally observed responses of algal strains will be used to validate and refine the model for life support systems simulation.

UTILIZATION OF NITROGEN SOURCES BY HIGHER PLANTS

Utilization of nitrogen sources by plants has been studied for the past 75 years. However, many of the data are unsatisfactory, due to unrecognized/uncontrolled variables in the experimental designs. It is generally agreed that the nitrate anion and the ammonium cation are the most important sources of nitrogen for most higher plants under most conditions. Of course, certain groups of plants such as the legumes participate in symbiotic associations with micro-organisms and thus gain indirect access to the diatomic molecular nitrogen of the atmosphere. But even here, it is only the microbial symbionts which can utilize the atmospheric nitrogen directly; the legume host actually receives its nitrogen in the form of ammonium ion. It has also been reported that certain plants can under certain conditions utilize other organic nitrogen sources such as urea, free amino acids, imido compounds, and even purines. But these are clearly minor sources in comparison to nitrate and ammonium ions.

All of the above statements raise the question whether nitrate or ammonium is the more important nitrogen source. The answer appears to depend on a number of factors. It has been shown utilization of

nitrate and/or ammonium is influenced by the pH of the growth medium, the aeration of the growth medium (availability of oxygen to the roots where the nitrogen source is being taken up), the amount of carbohydrate reserves available to the plant, the stage of development of the plant, and the species of plant. We are on shaky ground in trying to summarize all these factors into a few simple rules, but here are some (very rough) rules of thumb. Plants which have evolved in arid conditions on neutral or alkaline soils tend to utilize nitrate preferentially, and may even be inhibited or killed by moderate levels of ammonium. Plants which have evolved on acid soils or in mesic to humid conditions tend to utilize ammonium preferentially. Most agricultural plants do not fall neatly into either of the above categories, and can utilize either ammonium or nitrate. But among these agricultural plants, it appears that a common pattern is for the ammonium ion to be used preferentially by young plants; followed by a shift to nitrate utilization as the plant ages. This has been shown for oats, maize (corn), tomatoes, and white (Irish) potatoes. In addition, some plants appear to utilize ammonium preferentially throughout their lives, even when nitrate is available; such plants include pineapple and sugar beet and most tropical grasses. Other plants appear to utilize nitrate preferentially; these include barley, rye, wheat, and radish. However, there is a further complication. It appears that even among plants which utilize one nitrogen source preferentially, maximum growth rates are obtained only in the presence of both ammonium and nitrate ions. This appears to be true of wheat, maize (corn), soy bean, and tobacco (and possibly others). No specific information on sweet potatoes, lettuce, or strawberries has been found.

SUMMARY (SOMEWHAT OVERSIMPLIFIED)

Plants which utilize nitrate, obligatorially or almost so: Euphorbia, Jimson weed (Datura), cucumber.

Plants which utilize ammonium, obligatorially or almost so: healthier, azalea, rhododendron, laurel, honeysuckle, bay, blueberry(?).

Plants which can utilize either but prefer nitrate: barley, rye, wheat, radish, older oats, older maize (corn), older tomatoes, older white (Irish) potatoes.

Plants which can utilize either but prefer ammonium: pineapple, sugar beet, most tropical grasses, young oats, young maize (corn), young tomatoes, young white potatoes.

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SECTION III
INTERDISCIPLINARY RESEARCH

Chapter 5
**PLANT GROWTH UNDER LOW ATMOSPHERIC
PRESSURE**

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Chapter 5

PLANT GROWTH UNDER LOW ATMOSPHERIC PRESSURE

The experimental work reported here was sponsored by Dr. Donald H. Henninger, NASA Johnson Space Center, and funded under NASA Grant NAG 9-253. The idea for the work was developed through RECON Team discussions, and results are of direct interest to the life support systems being studied and are presented here for that reason. The interest and support of Dr. Henninger are appreciated.

The effects of low atmospheric pressure on higher plant growth were investigated to provide information useful for designing and developing plant growth systems for long-duration space missions and planetary space bases. Survivability and growth responses of radish (*Raphanus sativus*), at 1/20 atmospheric pressure (5 kPa) were compared to those at normal atmospheric pressure (100 kPa) in two types of low pressure chambers, closed system, and manually operated open system. In addition, germination and growth of maize (*Zea mays*) was compared at 1/5 atmospheric pressure (20 kPa) to that at normal atmospheric pressure in an automated and open low pressure system.

In the closed system (no net CO₂ available) young radish plants were able to survive low pressure at least 10 days if illuminated. No net growth could occur because no net CO₂ existed, however, growth resumed when normal pressure was restored and net CO₂ became available. In darkness, plants died quickly because they could neither photosynthesize (no CO₂) nor respire (O₂ partial pressure too low).

In the manual open system (net CO₂ available), two chambers were operated at normal pressure (100 kPa) and two at low pressure (5 kPa) with the partial pressures of O₂ and CO₂ in both approximately 5 kPa and 0.1 kPa, respectively. Young radish plants increased in biomass throughout an eleven day treatment period, although those at low pressure grew more slowly (due to leaf damage upon pressure transition). Plants in the normal pressure chambers accumulated more biomass than the non-enclosed control (probably because of the higher CO₂ partial pressure of 0.1 kPa vs. 0.035 kPa).

The automated and open low pressure system has been essentially completed, with the data acquisition component now fully automated. Using this system, maize seeds were successfully germinated at low pressure (20 kPa). Germination at low pressure was slightly accelerated compared to normal pressure, and thus early growth stages appeared similarly accelerated. However, twelve days after germination, we detected no significant differences in dry weight accumulation, or in the net uptake of CO₂ during growth,

of plants grown at 20 or 97 kPa. Further development of the automated low pressure chamber and further studies of plant growth in low pressure are planned for the future.

RATIONALE

There are three basic reasons to study plant growth under low atmospheric pressure. First, the ability to grow food plants at low pressure has important implications for the design, deployment, and operation of space-based plant growth facilities. The use of higher plants in long-term Moon, Mars, or orbital-based missions requires that relatively large areas be dedicated to their growth. If plants are grown at Earth's atmospheric pressure, then the plant growth facility must be capable of containing 100 kPa. If plants could be grown at reduced atmospheric pressure, however, then the structural requirements of a plant growth facility in space could be reduced. A reduced pressure differential between the plant growth facility and its external environment would permit less massive materials to be used in its construction. Reducing the mass of the plant growth facility would reduce the total lift-off payload required to deploy the facility. The material used in the construction of an extraterrestrial plant growth facility with a reduced pressure differential with respect to its environment could possibly be a flexible polymer instead of rigid materials, which would reduce the payload volume required for deployment. A lower pressure differential between the plant growth facility and its environment would logarithmically reduce atmospheric leakage from the facility to its environment. The lower total pressure of the plant growth facility would require less N_2 gas to be transported to supplement the physiologically active gases (CO_2 and O_2).

Second, plants in a space environment may experience large variations in pressure. In the interests of safety and reliability, it would be useful to characterize the response of plants in the event of an accidental or planned loss of pressure that could potentially destroy the higher plant food resources for a lunar base or other mission. Knowledge of plant responses to changes in pressure would be vital for defining operational protocols both for low pressure plant growth facilities and for emergency procedures in the event of depressurization. Plants grown under low pressure may experience less stress and have greater survivability during pressure changes or if the plant growth facility develops a leak and its total pressure approaches a vacuum.

Third, quite simply, very little is known about plant growth under low pressure. It is not fully understood how low pressure interacts with any number of environmental parameters and plant physiology to affect plant survival and biomass production. All of these points form compelling reasons to characterize plant growth and behavior at low pressures.

RESEARCH GOALS

The primary objective of this project was to grow plants at the same concentration ratios (moles/volume) of CO_2 and O_2 in the presence or absence of N_2 and determine if plant growth rate was affected by the pressure of the growth environment. We concentrated on growing plants at normal

atmospheric pressure (100 kPa), 1/5 atmospheric pressure (20 kPa), and at 1/20 atmospheric pressure (5 kPa). Our approach has been to select appropriate plant species, develop the apparatus necessary to grow the species under the defined environmental conditions, and then conduct increasingly more precise experiments. These steps are detailed below.

Choice of Plants

Two species of plants were chosen as test plants for investigation: radish (*Raphanus sativus*, cult. Cherry Belle) and maize (*Zea mays*, cult. Early Spring). Radish was chosen for the initial phases of the investigation for three advantageous properties: (1) it is well characterized physiologically in the literature, (2) it grows rapidly to harvestable size in two to three weeks, and (3) its stature (a rosette) remains relatively constant with plant growth. Later, maize was selected because of its rapid growth and ability to thrive in high-humidity conditions (which prevents the germination of radish plants). As we develop the ability to reduce and control the relative humidity in the plant growth chambers, we will again use radish plants.

Development of Low Pressure Plant Growth Chambers

The chamber development goal was to construct a plant growth chamber in which the concentration of CO₂, H₂O, O₂, and N₂ can be independently set, monitored, and controlled. The total pressure within the chamber is thus the sum of the constituent gases. Our chamber development effort was divided into three stages, the development of a closed-system low pressure chamber, a manual open-system low pressure chamber and an automated open-system low pressure chamber, respectively. These are described in turn.

Closed-system Low Pressure Chamber

The first development stage resulted in the basic plant chamber illustrated in Figure 1. This chamber is referred to as the closed low pressure chamber because gas exchange cannot occur between its interior and exterior once a partial vacuum is drawn. This chamber maintains an essentially complete vacuum. Its pressure half-life (the time required for 1/2 of an established pressure gradient to dissipate) exceeds three weeks. Similar closed low pressure chambers are the type of chamber in which all existing data on low pressure plant growth have been collected (e.g., Andre and Richaud, 1986).

Manual Open-system Low Pressure Chamber

To couple any plant growth facility into a CELSS, it is, of course, essential that the facility be open. We use the term "open" to indicate that gas exchange between the chamber and its environment can occur (generally under controlled conditions). Consequently, all remaining activity involves open chamber systems. The second stage was therefore the development of a manually-operated open chamber (Figure 2).

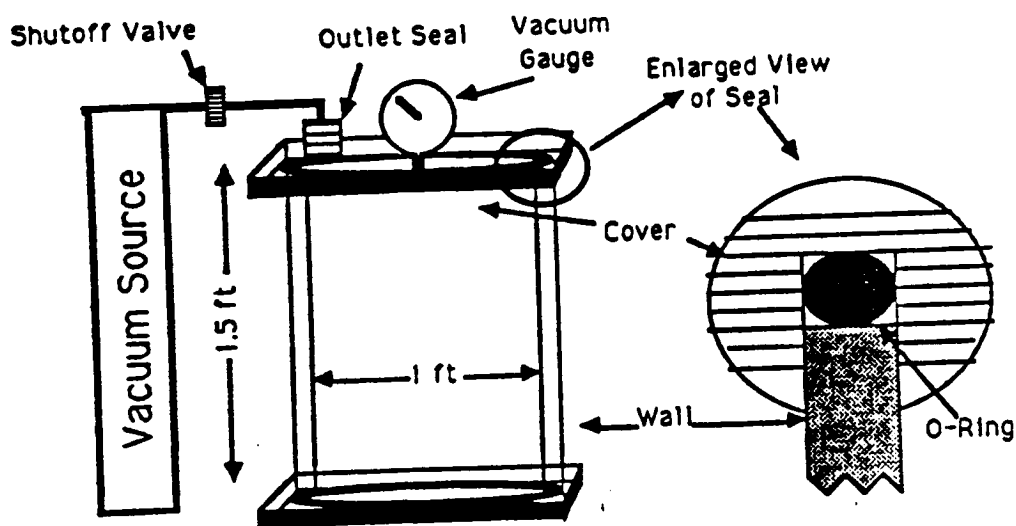


Figure 1. Closed low pressure chamber (LPC). The 1/4" plexiglass cylinder is sealed under vacuum to the 1" thick plexiglass top and bottom with an O-ring assembly.

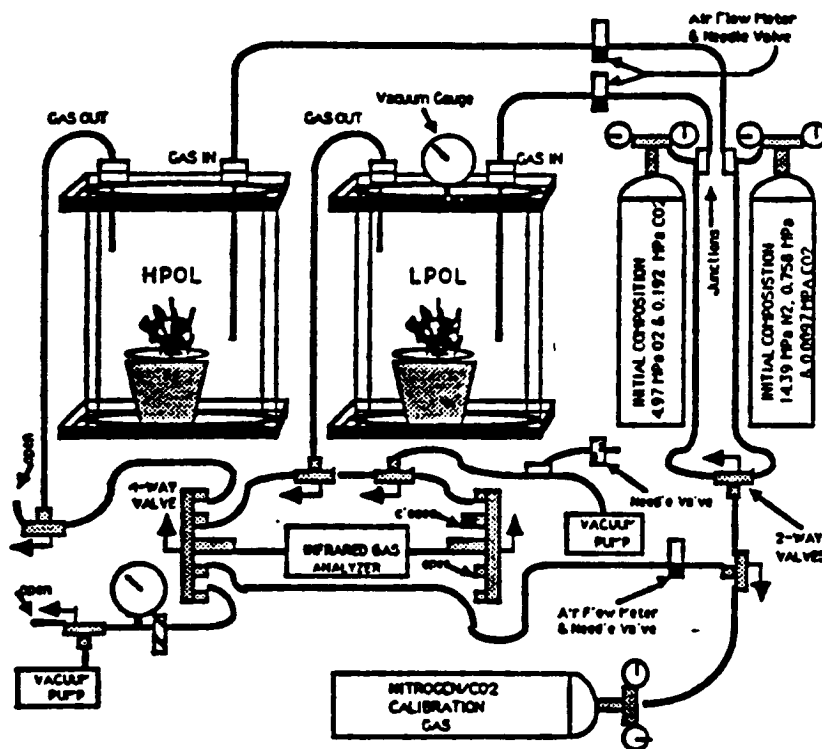


Figure 2. Illustration of the open manual low pressure chamber. The LPOL chamber is operated at 5 kPa and the HPOL chamber at 100 kPa.

Operation of the manual open low pressure chamber has demonstrated that we can control atmospheric composition at low pressure in an open system. We developed two chambers at 0.05 atmosphere and two chambers at 1 atmosphere in operation and compared plant behavior (see below).

Although the manual open low pressure chamber permits initial investigation of low pressure plant growth, it has certain limitations:

1. When operating at 5 kPa total pressure, a 1 kPa oscillation in pressure is common; this produces a 20% oscillation in the concentration of the constituent gases.
2. The desired composition of gases must be pre-mixed in high pressure gas tanks whose initial pressure is 150X that of the 1 atmosphere growth chamber, and 3000X that of the low pressure growth chamber. Thus, inaccuracies in the initial gas mixture are amplified. Therefore, producing an identical gaseous environment in both the high and low pressure growth chambers is difficult.
3. Unless the chamber is constantly monitored, the gas flow rate cannot be altered to compensate for changing metabolic activity of the enclosed plants. This causes additional oscillations in the concentration of the chamber's constituent gases.
4. The humidity within the chambers remains at nearly 100%, which lowers plant health.

Operation of the manual system has provided invaluable experience and insight for the design of an automatic system, and allowed us to conduct the first low pressure plant experiments with an open system.

Automated Open-system Low Pressure Chamber

The requirement for establishing and maintaining a defined atmospheric composition at multiple pressures led to the design of the prototype automated open-system low pressure chamber illustrated in Figure 3. The main features of the automated low pressure chamber are:

1. The complete control of the gaseous concentration of CO_2 , H_2O , O_2 , and N_2 obtainable in the chamber permits us not only to achieve the research goals of the current study, but also permits us to conduct future studies of how other gaseous constituents and pollutants (e.g., CO , O_3 , NH_3 , H_2S , H_2SO_4 , oxides of nitrogen (NO_x), etc.) affect plant growth and development.
2. Time-dependent alterations in the environmental gas composition of the enclosed plants can be programmed, and the effect on growth and development can be repeatedly determined.

The accuracy of measuring O_2 dynamics in our chamber will be very high relative to that of most plant growth chambers once our final design is achieved. Measuring O_2 dynamics is inherently less accurate than measuring CO_2 dynamics because the percent change of O_2 is four orders of magnitude less than that of CO_2 . This problem is corrected in our chamber by decreasing the mass flow through the chamber. Currently, the automated chamber can create a defined environment (i.e., N_2 , O_2 , H_2O , and CO_2

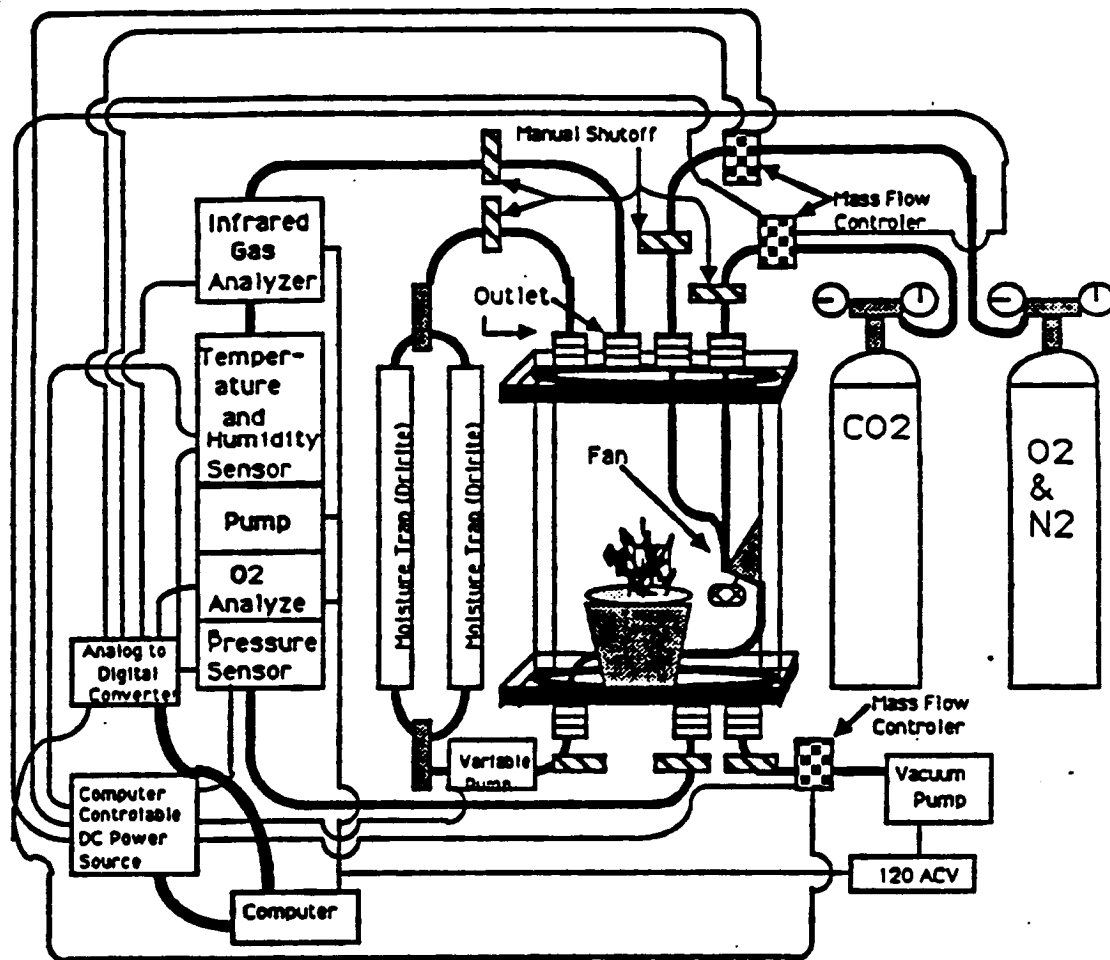


Figure 3. Illustration of the totally automated low pressure chamber.

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concentrations are constant). We cannot yet achieve a relative humidity of much less than 100%, however, and as yet have not been able to measure net O_2 dynamics.

EXPERIMENTAL RESULTS

Closed-system Low Pressure Chamber

Radish plants cannot grow in the closed low pressure chamber (Figure 4) unless excess CO_2 is provided. To assess whether radish plants could survive extended exposure (10 days) to low pressure (5 kPa) in the absence of net available CO_2 , we refrained from providing excess CO_2 in this series of low pressure experiments. The results show that they can, but only if illuminated. Radish plants in extended darkness (10 days) died quickly because they could neither photosynthesize (no light) nor respire (O_2 partial pressure too low).

Although no growth occurred during the closed low pressure treatment, the treated plants survived and continued growth at the treatment's end (Figure 4). There was about a one-third mortality, however, which appeared to be associated mainly with the transition to low pressure and not to the extended exposure to low pressure.

Manual Open-system Low Pressure Chamber

Gas exchange, and thus plant growth, occurs in an open system. We developed and placed into operation for manual open low pressure plant growth chambers.

In this experiment, we operated two chambers at 100 kPa and two chambers at 5 kPa. At both pressures the partial pressure of O_2 was 5 kPa while the partial pressure of CO_2 was approximately 0.1 kPa. Eleven-day-old radish plants were placed in each chamber (four per chamber), and a number of control radish plants were placed outside, but next to, the manual chambers. Four plants in each treatment group (control, normal pressure and low pressure) were harvested at intervals throughout an 11-day treatment period.

All treatment groups increased in dry weight with time (Figure 5). The plants in the normal pressure group grew slightly larger than the control (possibly the result of the higher CO_2 partial pressure, 0.1 vs. 0.035 kPa, respectively). The weight of plants in the low pressure treatment group was significantly less than plants in the control and normal pressure groups. The smaller size of the plants in the low pressure treatment group appeared to result from the leaf damage that occurred during the initial pressure reduction. This is suggested because of the size of those plants with less leaf damage approached the size of the plants in the control and normal pressure treatments.

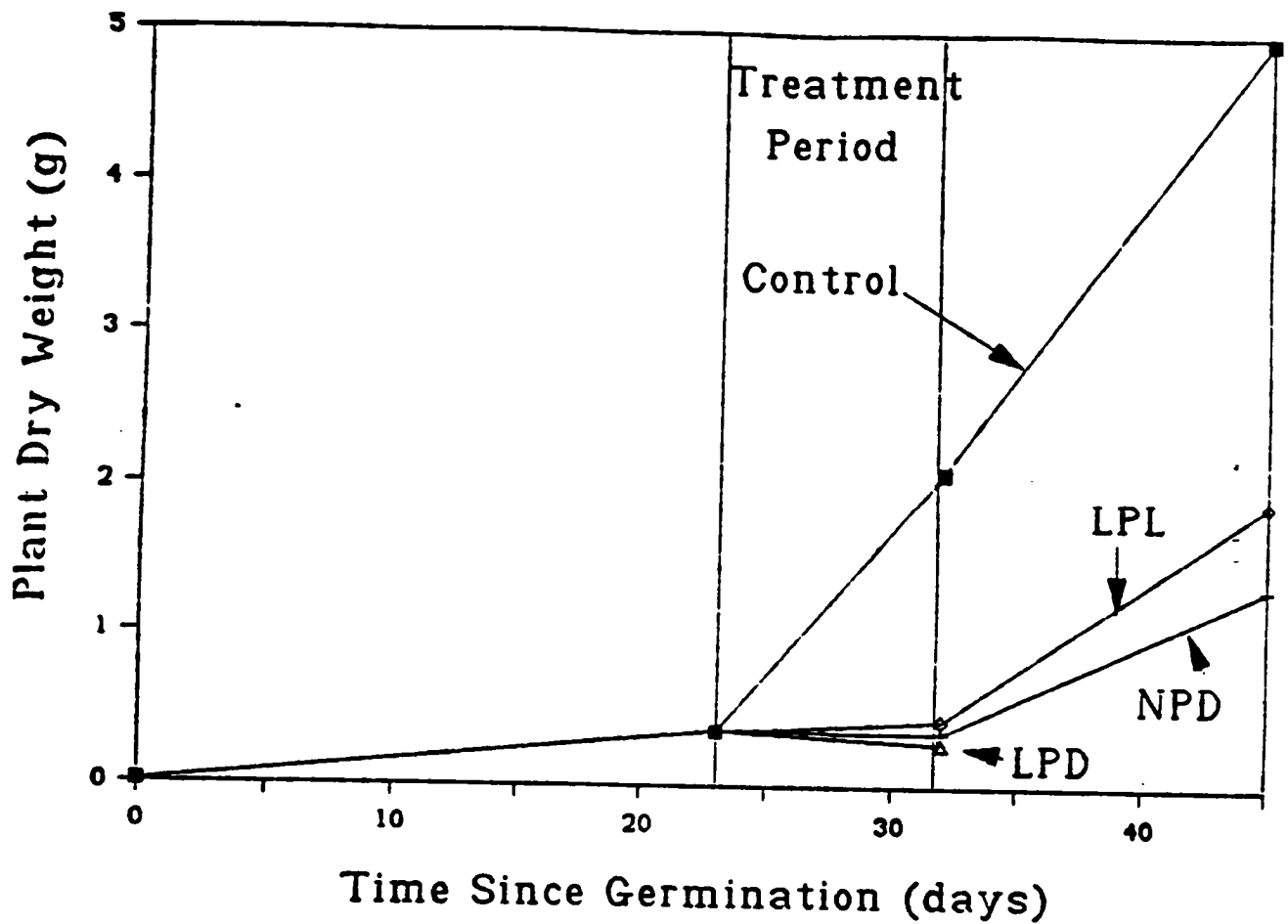


Figure 4. Radish plant dry weight is affected by low pressure treatment given between day 22 and 32 of growth. Control plants (dark square) were not enclosed within a chamber and received optimal growth conditions. LPL plants (diamond) were enclosed at low pressure (5 kPa) in light. LPD plants (triangle) were enclosed at low pressure in dark and they died during treatment. NPD plants (dash) were placed in the dark at 1 atm (100 kPa).

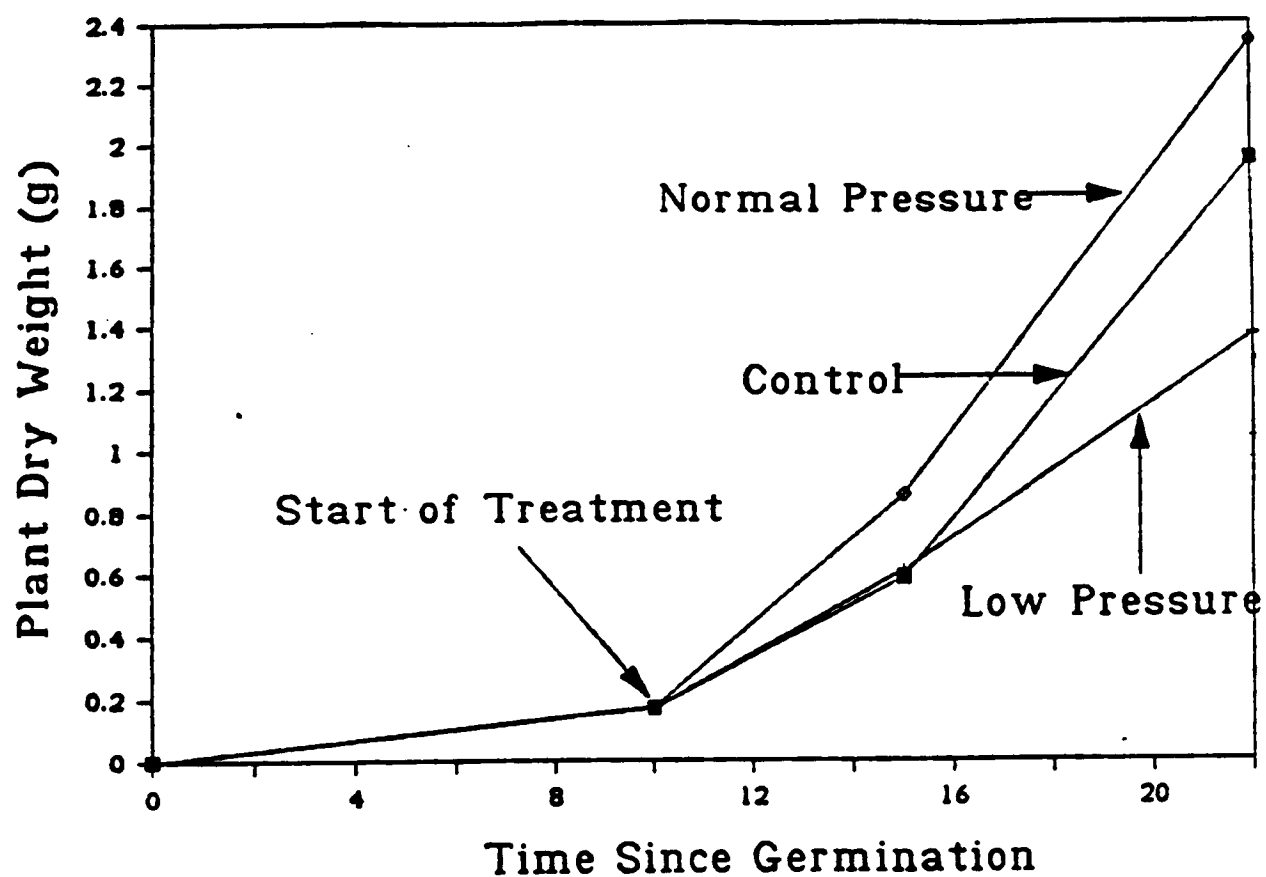


Figure 5. Effect of open low pressure treatment on radish plant dry weight gain (see text). The treatment was initiated on day 10 of growth and continued until the end of the experiment at day 22.

The leaves that developed during the low pressure treatment appeared similar to those developed by the control plants. This observation, together with the consistent occurrence of leaf damage during the initial pressure drop suggested that test plants should be germinated as well as grown under low pressure. The next development phase, implementing the automated low pressure chamber, investigated seed germination at low pressures.

Automated Open-system Low Pressure Chamber

The open-system automated low pressure system is now operational. Data acquisition is totally automated and if a single plant growth chamber is selected, then the mass flow through a chamber can be automated so that the concentration of constituent gases remains constant. We have at present four chambers in operation, but only a single instrument loop, therefore we must manually select the particular chamber for measurement. We cannot automatically control gaseous constituents in the non-selected chambers. This causes gas constituent concentrations to oscillate. In addition, we have not developed the capacity to reduce the relative humidity below near 100%, nor do we yet have the capacity to measure net O_2 dynamics.

With the above limitations, we have succeeded in germinating corn plants at 97 and 20 kPa in the automated plant growth chambers. The partial pressure in both treatments of O_2 and CO_2 were 20 kPa, and 0.06 kPa respectively. The germination of the 20 kPa treatment appeared slightly accelerated, but twelve days after germination both treatment groups had a final dry weight of about 850 mg with no significant treatment effects. The net CO_2 uptake during the twelve days of growth (Figure 6) shows that there was little difference between treatment groups. The slightly greater net uptake of CO_2 by the 97 kPa treatment is believed to result from unresolved calibration errors, and not from a property of the treatment itself. These calibration errors are being steadily reduced as we gain insight into the operation of our chambers. What is significant, however, is that in both treatments the increasing rate of net CO_2 uptake is identical. This indicates that both treatment groups have essentially the same growth response irrespective of the pressure in which they are grown.

At day 9 of the experiment, a sub-population of low pressure plants were placed in high pressure, and a sub-population of high pressure plants were placed in low pressure. Unlike the radish plants, which showed leaf damage upon reduction of atmospheric pressure, the corn plants showed no such leaf damage. This may be the result of the greater vascular strength of corn (a C_4 plant) versus radish (a C_3 plant). This phenomenon will be investigated further in the future.

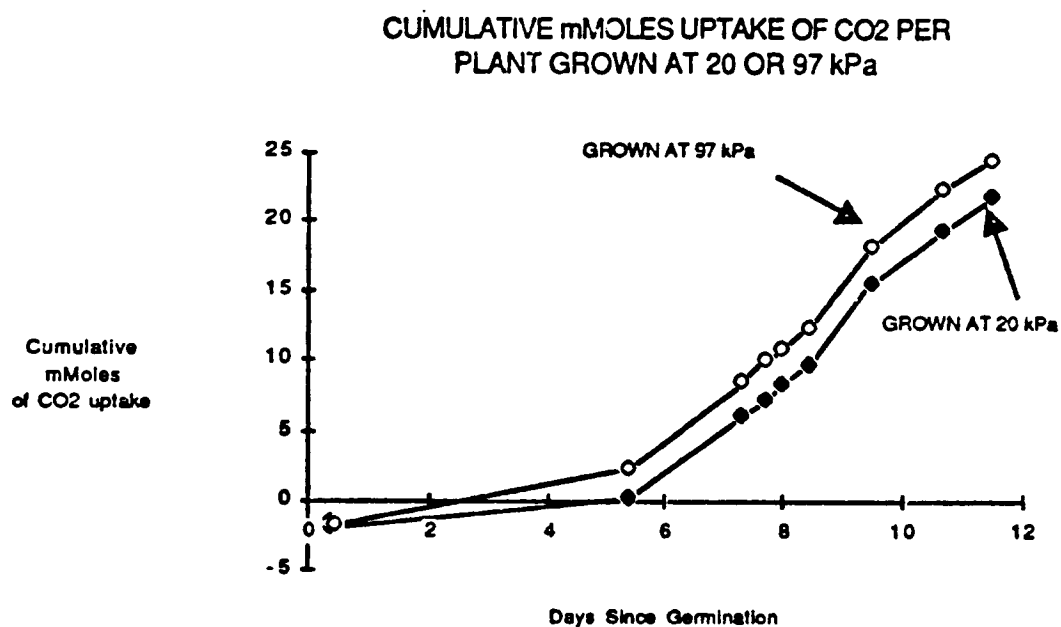


Figure 6. Cumulative uptake of CO₂ in maize plants as a function of atmospheric pressure, using the automated open-system low pressure system.

DISCUSSION

Effect of Pressure Changes on Plant Growth

The results of this project indicate that pressure changes are more damaging to plants than low pressure *per se*. It remains to be determined more fully whether plants grown in low pressure show more resilience to changes in pressure than plants grown under atmospheric pressure.

Leaf damage that occurs when a plant experiences a sudden decrease or increase in pressure (on the order of 95 kPa) must be quantified and related to the plant's growth stage (i.e. 2, 5, or 8 leaves) and previous growth pressure (100 or 5 kPa). This phenomenon is similar to how drought affects plant growth and development. In both cases plants acclimated to one set of environmental conditions experience tissue senescence when placed in an altered and more stressful environment.

Information about this phenomenon will become important to investigators developing higher plant cultivation and production practices for extraterrestrial closed ecosystems, particularly if plants are brought into pressurized regions for manipulation, or a sudden loss of pressure occurs in a plant growth facility and its atmosphere is released to the extraterrestrial environment.

Effect of Atmospheric Composition on Plant Growth

The CO₂, H₂O and O₂ concentrations, light intensity and temperature of the environment all affect plant growth, and each must be investigated to document fully plant growth at low pressure. Soil matrix factors (nutrient levels, CO₂ and O₂ concentrations, moisture levels and temperature) should also be investigated. Our preliminary results, however, show that plants can grow at low pressures with growth rates approximately comparable to plants grown at normal pressures.

FUTURE RESEARCH OPPORTUNITIES

Here we sketch our ideas for further research related to low-pressure plant growth. An obvious area for continued research, and one we see as the next stage of our studies, is the effect of temperature and light on low pressure plant growth. Specifically, we hope to investigate how temperature and light interact with atmospheric composition to affect plant growth and development.

A variety of questions about plant growth at both normal and low pressure can be addressed using the apparatus developed for this project. For example, what combinations of low pressure, temperature, and light regimes can be used to regulate plant growth to meet specific requirements for a CELSS? How will interspecies competition affect CELSS operation? How do other food plant species respond to low pressure? We envision including other species in future studies. Can a test protocol be developed for assessing plant fate following depressurization and repressurization? We think these should be important questions for future work.

SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 6

HIGHER PLANT GROWTH MODEL

Prepared by

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Industrial Engineering

Chapter 6

HIGHER PLANT GROWTH MODEL

HIGHER PLANT MODELING

Space colonies, particularly those on the moon, have the potential to establish plant growth facilities to close the ecological loop using natural biological processes. Specifically, plants provide an opportunity to regenerate oxygen from carbon dioxide, and food from waste (Fig. 1). It is premature to choose which processes can be best achieved by which species or even plant types. The final design will most probably involve a mixture of higher plant and algal species.

In this report, we present prototypes of two models, one for higher plants and one for algae. These models are quasi-mechanistic in that they emphasize the basic biochemical processes underlying plant growth. The models are generic in that they are not species specific. Particular species as they are selected will be parameterized from the list of recommended NASA species. These species are discussed elsewhere in this final report.

Optimizing Higher Plant Environments for Life Support in Space

The ideal space environment for plant production is not necessarily identical to that on earth. Plants evolved under quite different environmental conditions from those operating on Earth at present. The original environment was low in oxygen and high in carbon dioxide. Optimum plant performance will probably be found for gaseous compositions intermediate between primeval and current oxygen concentrations. The tradeoffs between oxygen demand for respiration, growth and reproduction must be placed against the inhibiting effects of oxygen at ambient and higher temperatures on photosynthesis through the process of photorespiration.

Plant growth models must be developed from a minimum factor set (Table 1) which includes the 13 mineral elements, oxygen, carbon dioxide, water status (especially for plants growing in lunar soil, but less important for hydroponic growth), light, relative humidity, air temperature, root temperature and calculated leaf temperature. The model calculates five interdependent biochemical process rates within the plant. The five interdependent process rates are: resource acquisition and capture, assimilation of photosynthate, respiratory maintenance, transport and allocation of photosynthate. These processes are tightly coupled and demonstrate adaptive feedback control. Ideally, they should be structured holistically within a single conceptual framework. In this way, the model structure resembles the functional structure of the plant. The desirability for similarity in structure becomes more important as the level of interaction increases in response to multifactor stresses.

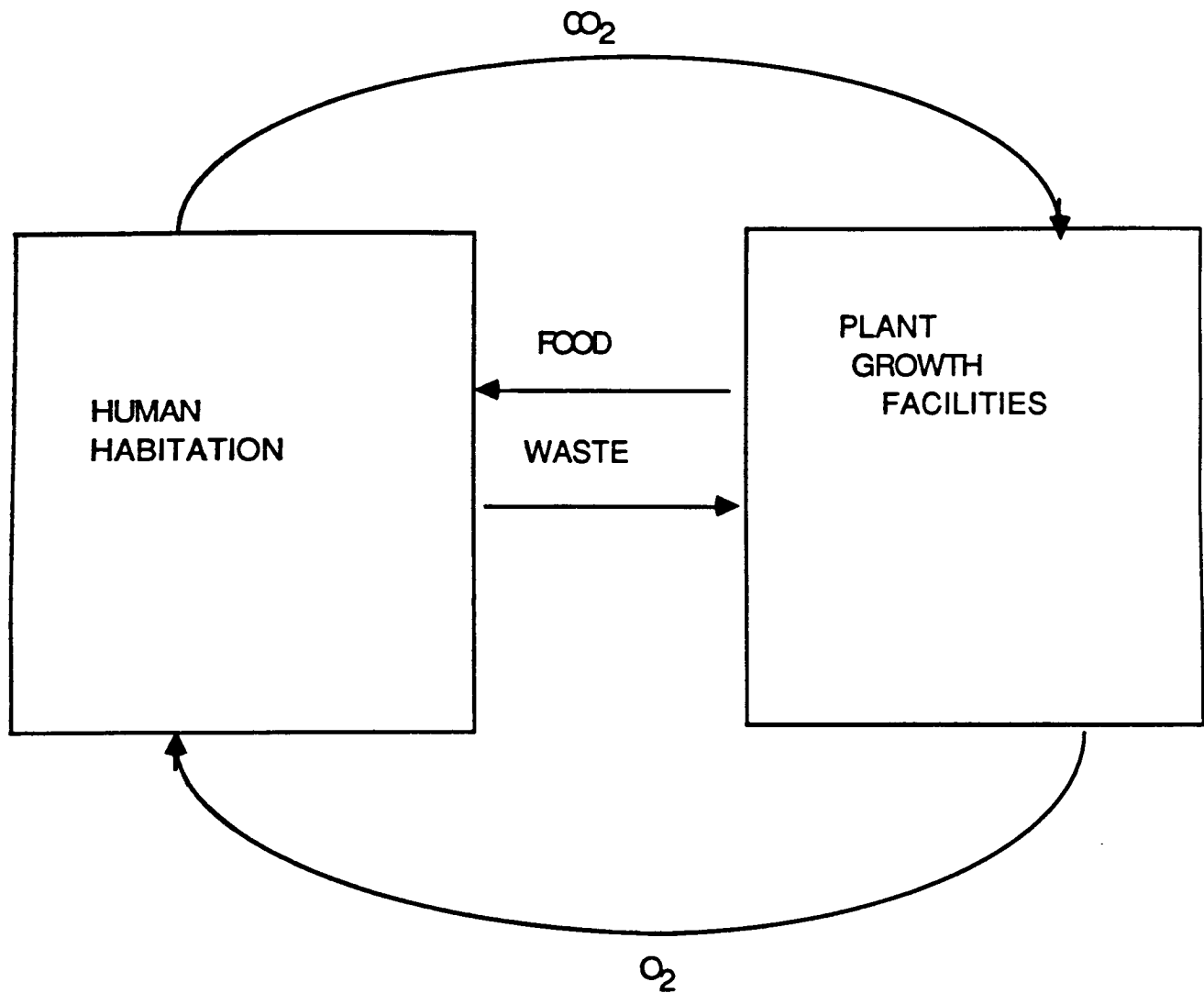


Figure 1. Ecological closure using higher plants.

Table 1. Minimum Factor Set

MINIMUM FACTOR SET:

1. Light - PAR.
2. Ambient CO₂, O₂, Relative Humidity.
3. Soil Water Availability - 3 layers.
4. Nutrient Availability - 13 mineral elements
N P K S Mg Ca Mn Fe Cu Mo B Zn Cl
5. Nutrient Excess Interactions.
6. pH, Al, Na, Se Toxic Interactions
7. Temperature:
Ambient Air, Soil,
Leaf (calculated).
8. Plant Functional Type - sets internal plant parameters

Adaptive physiological mechanisms enable plants to adjust to altered conditions of resource availability. Three of these mechanisms are relevant to this study: cyclical processes with dynamic pools, carbon flow homeostasis regulated by relative humidity, and compensatory allocation of photosynthate. These three mechanisms form the basis for modeling interactions between natural and anthropogenic stresses.

Cycles with Dynamic Pool Sizes

Biochemical processes can be viewed either as linear pathways or regenerative cycles. From a linear pathway viewpoint, biochemical substrates enter in one form and emerge in another. A deeper look into the mechanism of biochemical processes reveals the widespread occurrence of regenerative cyclical processes with dynamic pool sizes. There is a hierarchy of nested cycles spanning many levels. Biophysical/biochemical cycles at four levels, particle, molecular, pathway and whole plant are presented as illustrations. Particle cycles include both electron and proton (H⁺) transport systems. These two systems

are coupled in Figure 2 to form the cyclic photophosphorylation processes in the grana of chloroplasts. In this cycle, electrons released by splitting water in photosystem II are recycled between high and low energy levels in photosystem I. Energy in the form of incident photons raises the free electron to a higher energy state. This energy is used to transport protons into the inner regions of the thylakoid. The gradient of protons across the thylakoid membrane creates an electric potential for ATP synthesis. The overall result of these two particle cycles is the synthesis of ATP from light energy.

At the next level, enzyme reactions involve a cyclic process of enzymes changing from the free state with arrival of substrate to enzyme-substrate complexes. Release of product returns the enzyme to the free state again (Fig. 3). At the metabolic level, Calvin cycle enzyme reactions regenerate C₅ carbon skeletons which combine with CO₂ to form two C₃ sugars. The Calvin cycle is driven by input of chemical energy in the form of NADPH and ATP. Six revolutions of the cycle result in the synthesis of C₆ sugars (Fig. 4).

Whole plant cyclical processes are also evident. The translocation cycle (Fig. 5) circulates water and inorganic ions (such as potassium) to transport carbon from leaf synthesis sites to growth sinks. This cycle is driven by active loading of sugars and inorganic ions in the leaf. Osmotic pressure causes the sugar water solution to move by mass flow along the phloem sieve tube element. The water potential difference between the xylem and phloem causes additional water to enter the phloem, resulting in increased velocities and decreasing concentrations (Goeschl *et al.*, 1976; Magnuson *et al.*, 1979). Potassium ions are recycled in the translocation cycle, or if leached from the leaves, by nutrient cycling in the ecosystem.

A synthesis of metabolic cycles at the whole plant level is shown in Figure 6. Additional cycles include the Tolbert, glycine-serine-NH₃, Krebs and amino-acid synthesis cycles. The dependence of these coupled cycles on inputs of water, light, nutrients and carbon dioxide is shown. Integration of resource inputs occurs by coupling of cyclical processes, regulated by dynamic metabolic pools. From a modeling viewpoint, it is not the identity of these innumerable intermediate compounds that is important, but the manner by which the overall system is structured to be regenerative and self-regulating.

Carbon Flow Homeostasis Regulated by Relative Humidity

Cowan (1982) presents a theoretical model describing how a plant may optimize water use in relation to carbon gain. More recently Ball *et al.*, (1987) found empirically that stomatal conductance to water vapor g_{sw} varies directly with assimilation rate A scaled by relative humidity at the leaf surface h_s , and inversely with the mole fraction of CO₂ at the leaf surface C_s :

$$g_{sw} = k A \frac{h_s}{C_s} \quad (1)$$

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CYCLIC PHOTOPHOSPHORYLATION

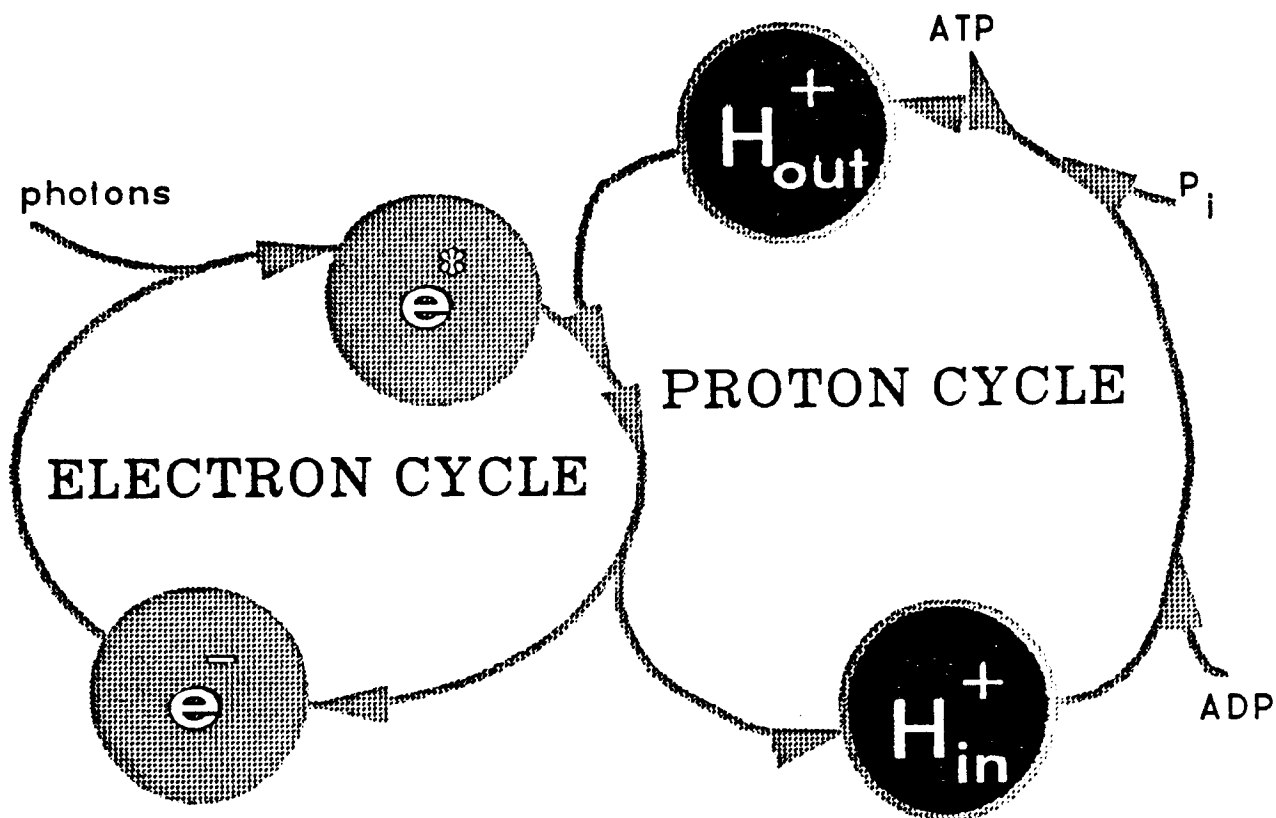


Figure 2. Electron and proton transport systems which form the cyclic photophosphorylation system.

ENZYME REACTION CYCLE

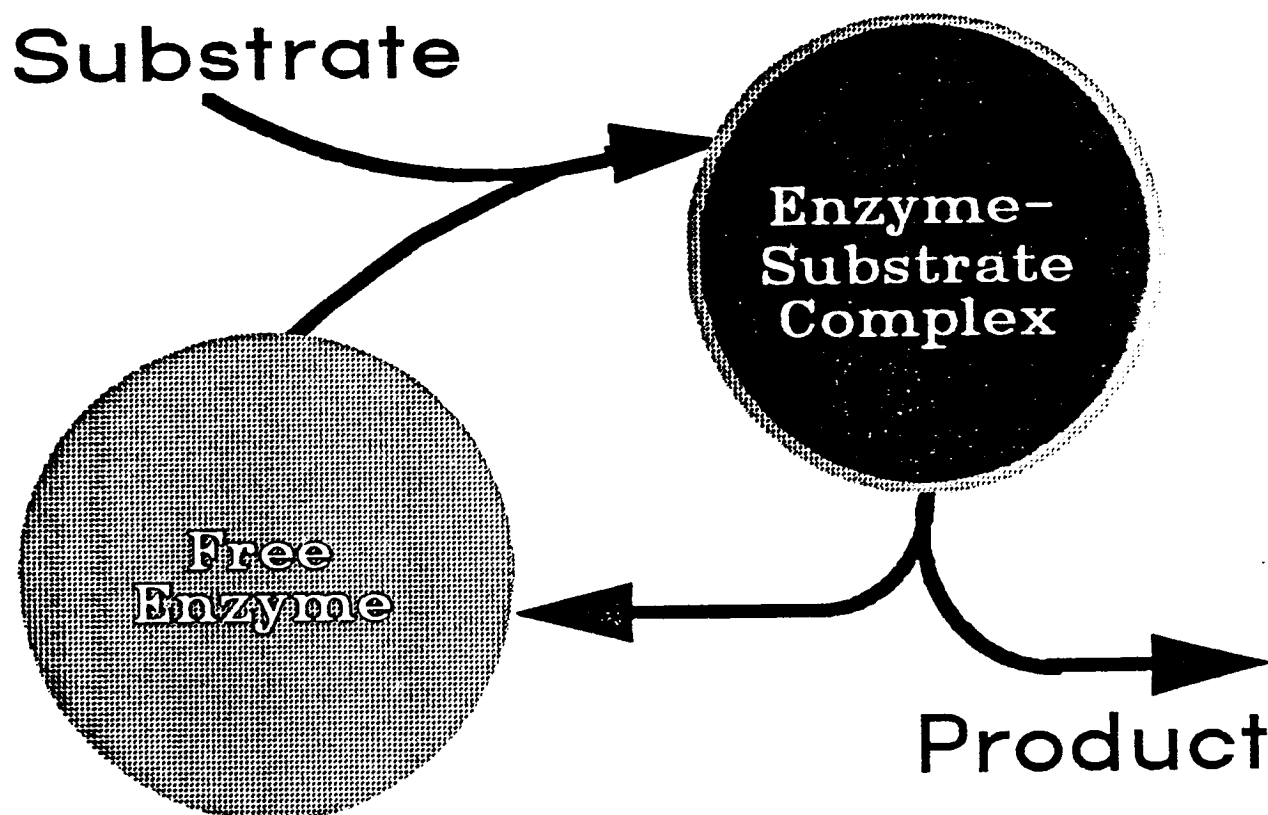


Figure 3. Enzyme reaction cycle with two states: free enzyme and enzyme-substrate complex.

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CALVIN CYCLE

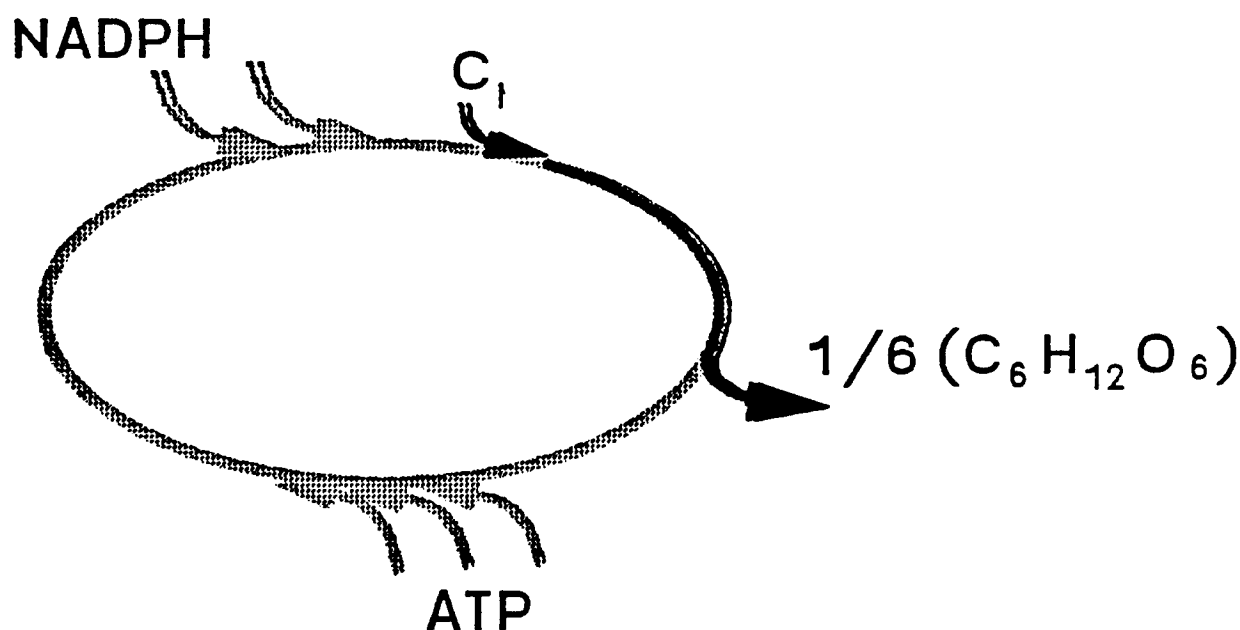


Figure 4. Calvin cycle showing energy input in form of a NADPH and 3ATP. Inputs to cycle are carbon dioxide (C_1) with C_6 sugars as outputs.

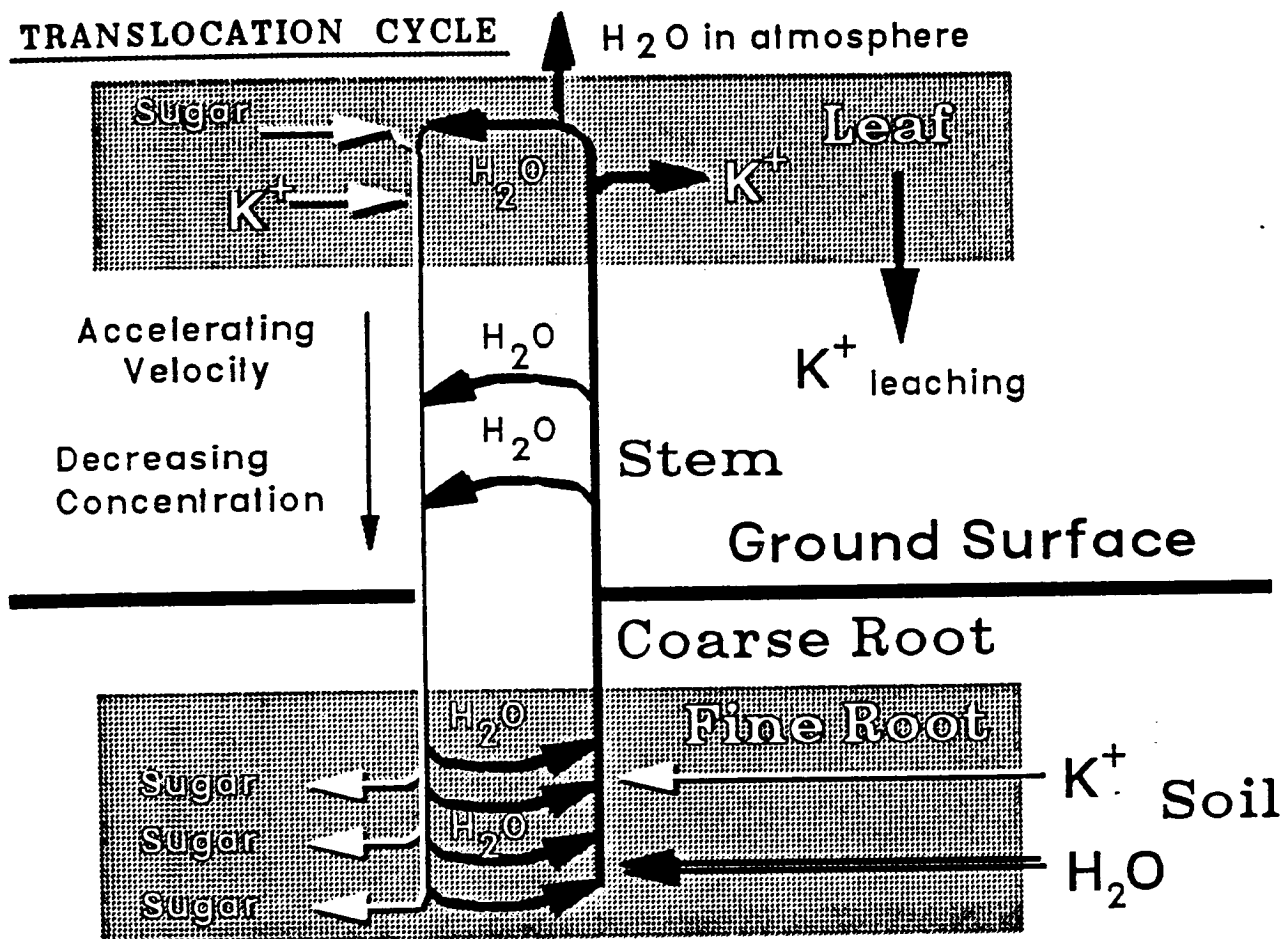


Figure 5. Translocation cycle showing transport of sugars by cyclical movement of water and monovalent ions such as potassium.

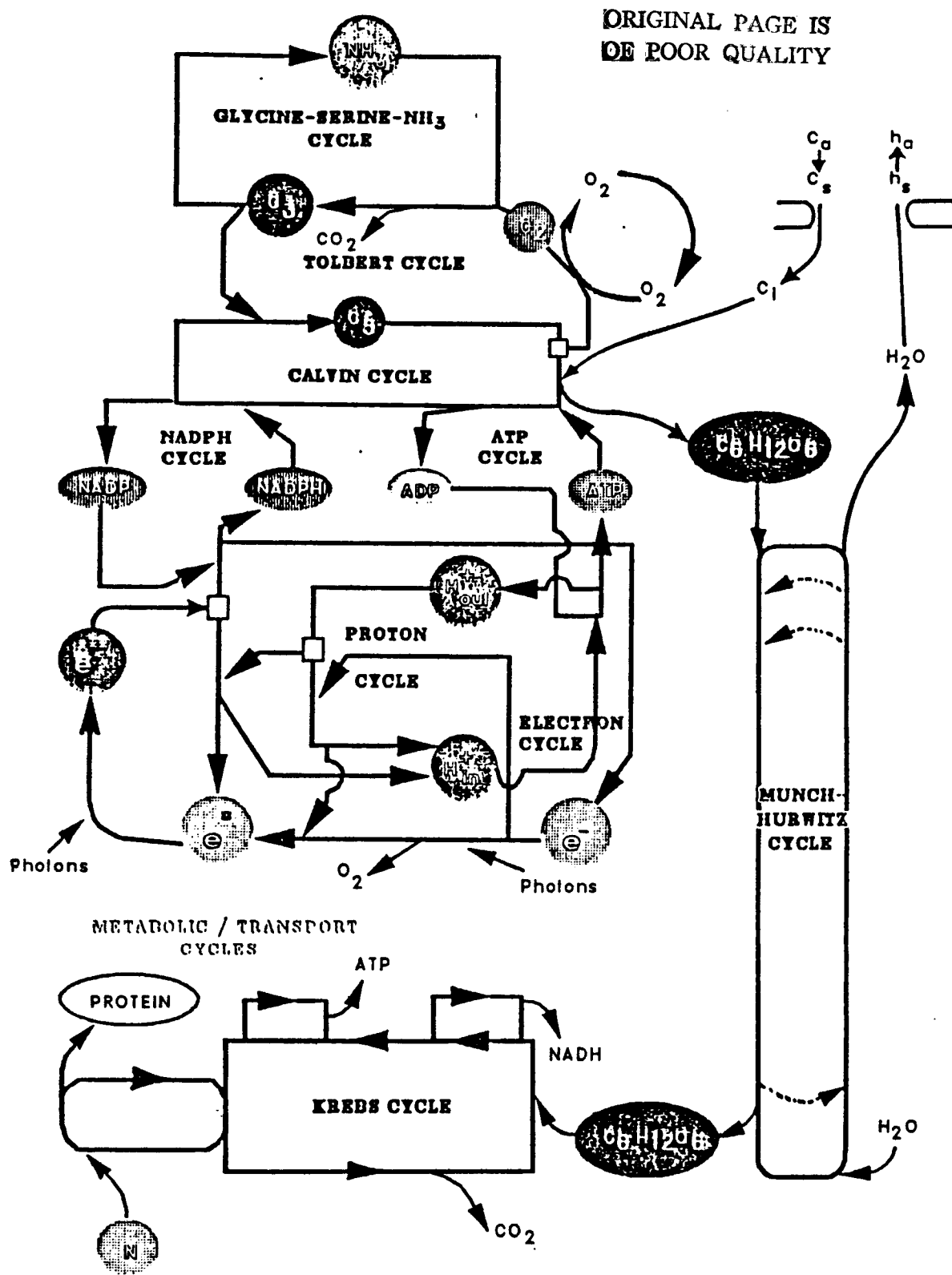


Figure 6. Coupling of selected metabolic cycles involved in plant growth and metabolism.

where k is a proportionality constant. In this form, however, the relationship is difficult to interpret and apply.

The carbon dioxide gradient equation can be written:

$$\begin{aligned} A &= g_{sw} (C_s - C_i) \\ &= g_{sw} C_s \left(1 - \frac{C_i}{C_s}\right) \end{aligned} \quad (2)$$

where C is the internal carbon dioxide concentration. Comparing eqs. (1) and (2) reveals the nature of the empirical dependency:

$$\left(1 - \frac{C_i}{C_s}\right) = \frac{a_c}{h_s} \quad (3)$$

where a_c is equal to $\frac{1}{k}$. Equation (3) implies that the level of internal carbon dioxide C_i within the leaf is regulated by the surface relative humidity h_s . Although the mechanistic basis for this regulation is unknown, it is consistent with the necessity for the plant to adjust to adverse environmental conditions. In this case, reductions in relative humidity cause a corresponding reduction in C_i . Furthermore, rearrangement of equation (1) yields

$$A = a_c \frac{C_s}{h_s} g_{sw} \quad (4)$$

In other words, when h_s and C_s are held constant, C_i is maintained constant such that carbon assimilation rate A is proportional to stomatal conductance. This we interpret as an adaptation to ensure carbon availability with minimum water use.

Compensatory Allocation

Bloom *et al.* (1985) found that plants characteristic of resource-rich environments are highly flexible in their allocation in response to environmental stress. In contrast, plants from poor environments typically respond by increased storage.

In resource rich environments, resource availability is spatially and temporally heterogeneous, depending upon the degree of competition from other plants. Thus a highly flexible pattern of compensatory allocation enables the plant partially to overcome the resource limitation. Specifically, these plants respond homeostatically to resource imbalances by allocating new biomass to organs capable of increasing the acquisition of resources that currently most strongly limit growth (Mooney, 1972). Bloom *et al.* (1985) document situations where light and carbon limitations result in proportionally more shoot and less root material. Conversely, nutrient stress leads to increasing proportional allocation to root growth. Water stress

can cause either an increase or decrease in root: shoot allocation, depending upon the species and the severity of the stress.

In summary, allocation is adjusted between roots and shoots in response to resource or environmental stress in a manner to maximize the capture of the most limiting resource. Ultimately, "plants adjust their allocation so that their limitation of growth is more nearly equal for all resources" (Bloom *et al.*, 1985). The alternate hypothesis which has been widely used in plant growth models is Liebig's law of the minimum. Liebig's law is based on one resource limiting growth at any one time. The compensatory allocation hypothesis which found by Bloom *et al.* (1985) to describe growth in relation to resource limitations more accurately than the Liebig law.

CRITERIA FOR MODEL STRUCTURE

Given that model structure should be determined by physiology, the following design criteria are applicable:

1. inputs: water, carbon, light, nutrients and temperature
2. physiological processes: growth and maintenance
3. structure: characteristic states
4. allocation: compensatory
5. outputs: root and shoot biomass

These are the essential elements. The challenge is to construct a simple model that encapsulates these essential features.

The most difficult component is the selection of metabolic intermediates. There are approximately 10^3 different enzymes and substrates in a typical cell. Figure 6 shows 13 cycles with approximately 10^2 substrates. Clearly any attempt to represent metabolic cycles and substrates realistically will generate overwhelming complexity. The essential function of these cyclical processes, however, can be conceived as being distributed among a defined set of characteristic states representing generic intermediates.

This approach has a number of advantages. The whole plant can be represented by five states. Transitions between states are regulated by availabilities of resources or completion of essential physiological processes. The complete model can be represented in one master equation. Only a small number of reductionist relationships and process constants are required. This approach is termed integrated rate methodology (IRM), as it involves a significant extension of the assumptions and procedures of more traditional mathematical approaches.

Antecedents of the basic IRM procedure appear in Sharpe and DeMichele (1977), DeMichele *et al.* (1978) and Sharpe (1983), which were further developed by Sharpe and Wu (1985), Sharpe *et al.* (1985, 1986, 1987) and Olson *et al.* (1985). The procedure is still in the process of development. Each application provides new insights into the power of this mathematically simple approach. In the traditional approach, models are constructed from individual reductionist and empirical relationships. These equations are

integrated in a cumberson synthesis algorithm. In the IRM approach, the holistic structure of the model is defined by the number and arrangement of characteristic states, and the regulation of transition rates between these states. Reductionist insights and relationships are used where applicable.

In its simplest form, growth can be viewed as a three-step cyclical process (Fig. 7). The four transition processes in the growth cycle (Fig. 8) are regulated by light, carbon, water and nutrient availability, respectively. The two transitions of the maintenance cycle are regulated by temperature and biomass maintenance demand. The reverse transition from one to zero represents photorespiration in C₃ plant species (Fig. 8).

The biophysical rational of the IRM plant growth model is based upon the following assumptions:

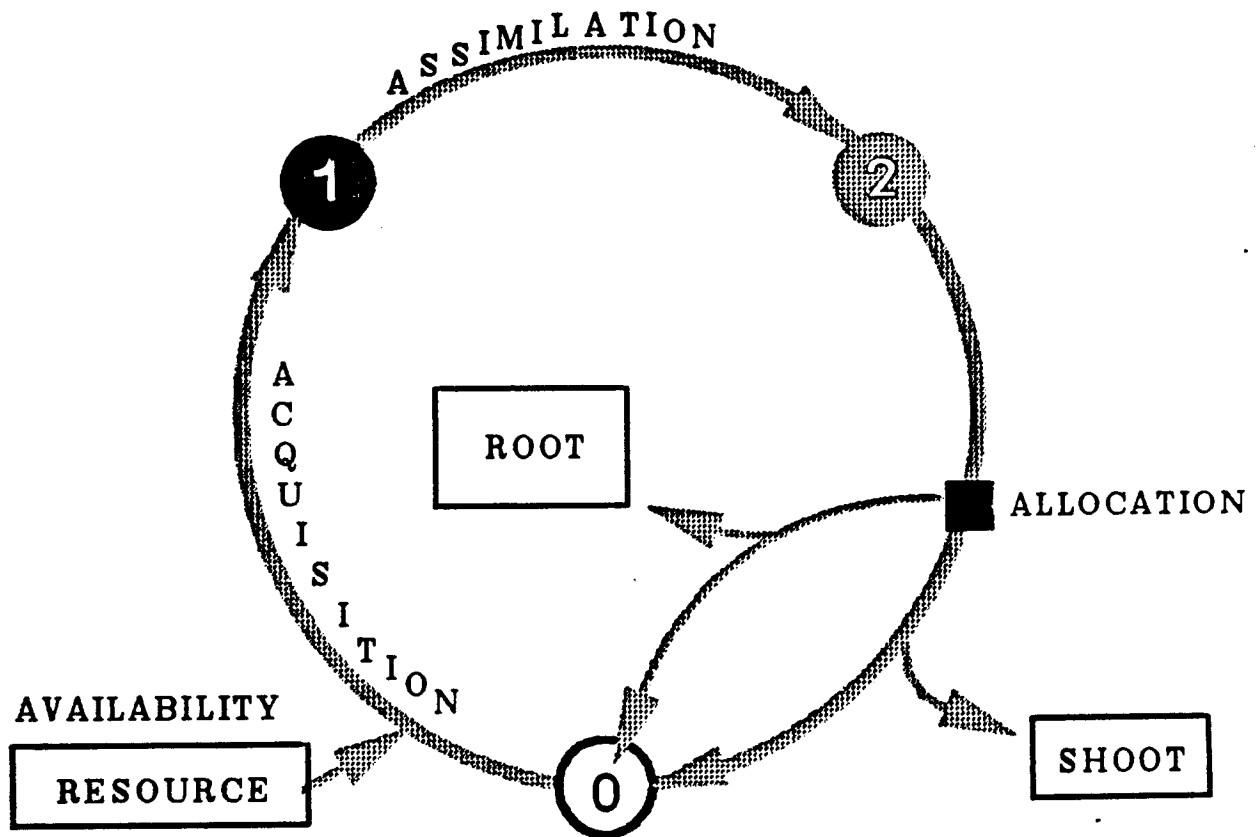
1. Transitions between states 0 and 1 are proportional to intensity of photosynthetically active radiation (PAR). This transition represents light absorption by photosystems I and II, yielding oxygen.
2. Transitions between states 1 and 2 are dependent upon carbon dioxide availability. The carbon availability is given by the right-hand side of equation (4) (see Ball *et al.*, 1987).
3. Transitions between states 1 and 0 are in competition with transitions between states 1 and 2. The relative rates of carbon dioxide uptake and photorespiratory release of carbon dioxide are dependent upon the relative RUBP carboxylase-oxygenase affinities for CO₂ and O₂, and internal concentration of both gases.
4. Transition rate between states 2 and 3 is a function of soil water availability.
5. Transition rate between states 3 and 0 is dependent upon nutrient availability. This transition also reflects the biomass synthesis and allocation step.
6. The branch in transition between state 3 and 0 addresses root and shoot growth-respiration, and biomass growth increments.
7. Transitions between states 0 and minus -1 represent respiratory maintenance, which is a function regulator in transitions 0 → 1, 1 → 0, 1 → 2 and 2 → 3 (see Sharpe, 1982).
8. Transition from state -1 to 0 reflects biomass catabolism to satisfy requirements for root and shoot maintenance.

This model structure follows the outline presented in Sharpe *et al.* (1985, 1986, 1987) with the addition of the carbon regulated step from states 1 to 2, and the branch allocation step from states 3 to 0.

MODELING RESOURCE ALLOCATION

The optimum resource allocation hypothesis states that plants respond homeostatically to resource availability imbalances by allocating new biomass to organs that enhance the acquisition of resources that most strongly limit growth (Bloom *et al.*, 1985). Resource availability is scaled from 0 to 1, where 1 represents the point on the growth curve at which this resource first becomes saturating. From this scale, a

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Simplified Growth/Transport Cycle

Figure 7. Growth viewed as a three-step cyclical process: resource acquisition, assimilation and allocation.

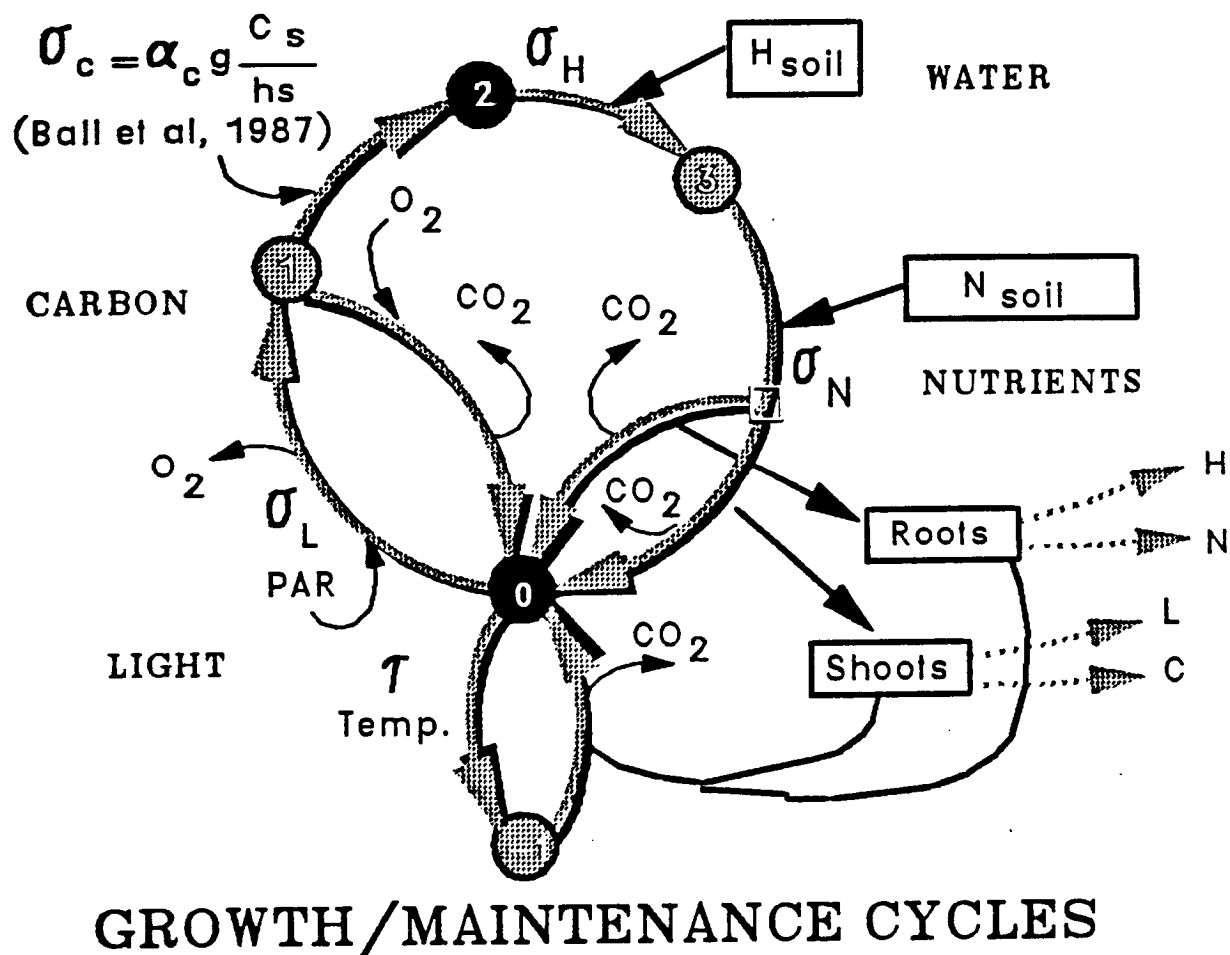


Figure 8. Transition diagram for growth-maintenance cycles with transition rates regulated by light, oxygen, carbon dioxide, water, nutrients and temperature.

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relatively simple equation can be used to describe allocation. The root and shoot biomass fractions, F_r and F_s , are calculated:

$$F_r = \frac{\kappa(L + C)}{L + C + H + N} \quad (5)$$

$$F_s = 1 - F_r \quad (6)$$

where L, C, H and N are fractional availability of light, carbon, water and nutrients, respectively, κ is the species allocation coefficient for roots under non-limiting resource conditions. The behavior of this equation is shown in Fig. 9. It should be noted, however, that as any resource goes to zero, so does the total growth increment calculated from the integrated rate growth model. Therefore, although the values of the allocation equation at extremely low resource values may appear unrealistic, the absolute magnitude of the growth increment is very small. It is in the intermediate range of resource availability that the function must be judged.

MECHANISTIC BASIS FOR RESOURCE ALLOCATION

To understand cause and effect responses to anthropogenic stresses, the mechanistic basis for resource allocation must be examined. The phloem translocation system modulates allocation within the plant and establishes the concentration of sink substrates for synthesis pathways in growth regions. Extensive experimental and theoretical studies have shown that phloem carbohydrate concentration and mass flow velocity are the dynamic variables of interest (Goeschl *et al.*, 1976; DeMichele *et al.*, 1978; Fares *et al.*, 1978; Magnuson *et al.*, 1982). Recent experimental studies (Goeschl and Magnuson, 1986 and Magnuson, *et al.* 1986) have confirmed the biophysical validity of the Munch-Horwitz hypothesis of phloem transport under normal temperature conditions.

This understanding of phloem transport mechanisms can be used as a base for proposing a set of hypotheses to explain the compensatory allocation mechanism. Light or carbon stress causes a reduction in carbohydrates and an increase in nutrient content (Bloom *et al.*, 1985). A reduction in carbohydrate decreases phloem loading rate, osmotic pressure and mass flow rate. Thus, carbohydrate export rate to roots is reduced, favoring shoot growth.

Conversely, nutrient stress leads to low concentrations of limiting nutrients and to accumulation of carbohydrates. As a result, phloem loading rate, osmotic pressure and mass flow velocity all increase. A significant increase in the carbohydrate export rate to root is predicted, which is unfavorable to shoot growth.

In each of these stress scenarios, the predicted outcome has been unambiguous. In the case of water stress, however, the result is conditional. Water stress has two effects on phloem transport. It leads to an accumulation of carbohydrates as for nutrient stress. In addition, water stress reduces the mass flow velocity

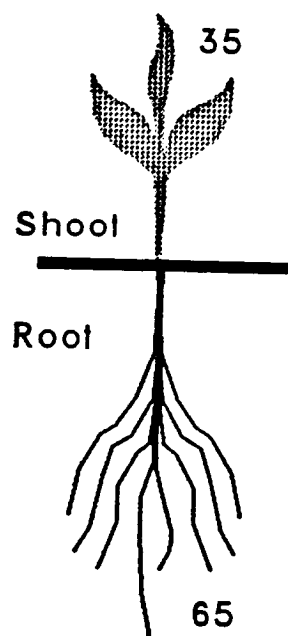
WATER LIMITED

$L = 90\% \text{ max.}$

$C = 80$

$H = 10$

$N = 80$



LIGHT LIMITED

$L = 10$

$C = 80$

$H = 100$

$N = 80$

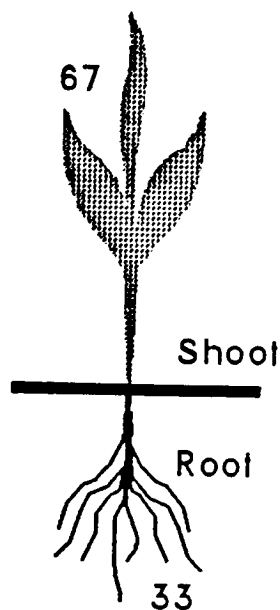


Figure 9. Illustration of allocation as a function of limiting water and light as defined in Equations (5) and (6).

by reducing plant water potential and phloem turgor. The allocation pattern is therefore dependent upon whether the concentration increase is greater or lesser than the reduction in velocity.

These predictions agree completely with the conclusions of Bloom *et al.* (1985) in their review of experimental results. Additional supporting evidence from water stress studies on phloem concentration and velocity by Goeschl *et al.* (1984) support the conditional hypothesis. A sample of their experimental results are shown in Fig. 10 and 11. The experimental protocol involved using high energy short-lived radioisotopes of carbon to measure cotton and corn photosynthesis and translocation responses to increasing levels of water stress, followed by rewatering.

The experimental results shown in Fig. 10 begin on day 1 when watering was stopped. The values of the control and water stress treatment plants were normalized for this day. Data for subsequent days are plotted as percent differences from the control. On the second day transpiration was slightly higher, which is consistent with predicted changes in stomatal conductance caused by the mechanical advantage of the epidermal cells (DeMichele and Sharpe, 1973; Sharpe, Spence and Wu, 1987). On days 3 and 4, both photosynthesis and transpiration decrease, but transpiration is reduced more. Following rewatering, both photosynthesis and transpiration approach the control. These results are consistent with other experiments in the literature.

The experimental data using C-11 short-life isotopes for measuring phloem transport response to water stress is shown in Fig. 11. As predicted, the phloem carbohydrate concentration increases leading to an accumulation of carbohydrate in the leaf. Also as predicted, the phloem transport velocity decreased. Rewatering initiated a return to the transport patterns of the control plant.

In conclusion, the concepts underlying a mechanistic interpretation of the optimum resource allocation hypothesis are completely consistent with the experimental data currently available. Although additional confirmatory studies are desirable, in our opinion a reasonable foundation exists for understanding and interpreting the mechanistic basis for responses to anthropogenic stresses.

Mathematical Structure of Higher Plant Model

The higher plant growth model was constructed according to the integrated rate methodology (IRM) developed by Biosystems Research Group, Department of Industrial Engineering, Texas A&M University. An IRM network consists of states and transition pathways. The system under study is considered to have numerous identical individual units, which may be termed systems constituents. For a given steady state period, fraction of system constituents in a given state i is unchanged. An IRM network does not have a one-to-one correspondence to the real system being studied; rather, it functionally reflects the overall dynamic behavior of the system.

The overall model consists three sub-models: (1) plant IRM and (2) soil water availability (3) nutrient IRM availability. For hydroponix plant growth, the soil water component is set to one provided it is well aerated.

WATER STRESS: COTTON

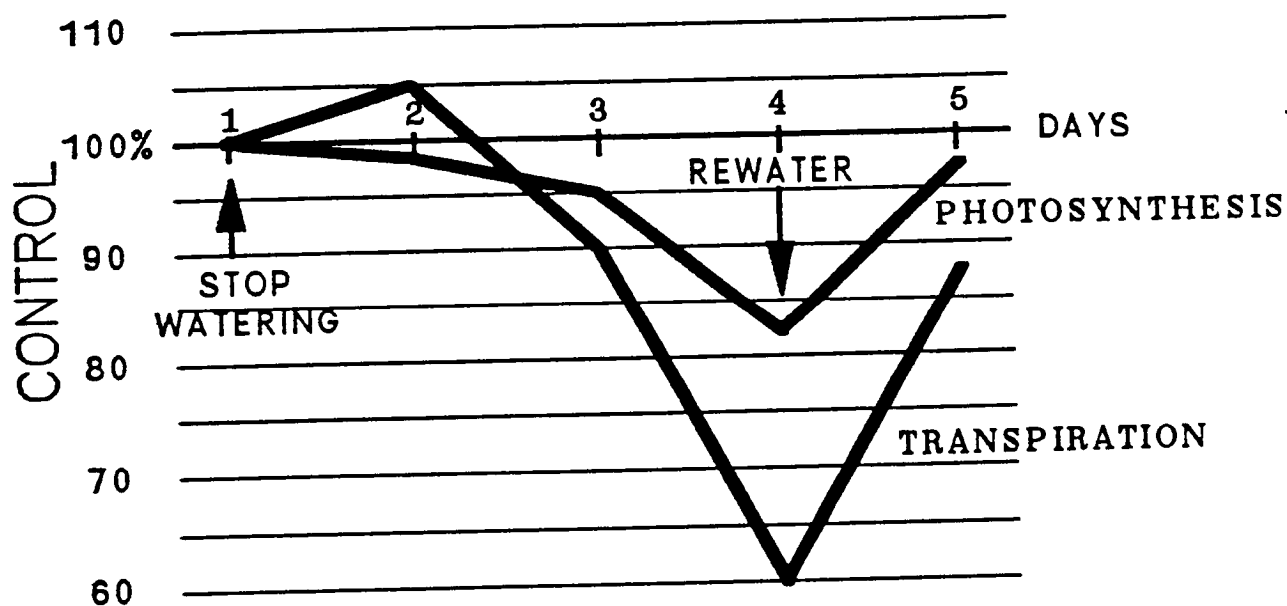


Figure 10. Experimental results from short-lived radioisotope study of cotton subject to 4-day water stress and recovery regime. Data shows effect of water stress on photosynthesis (carbon dioxide uptake) and transpiration (water loss).

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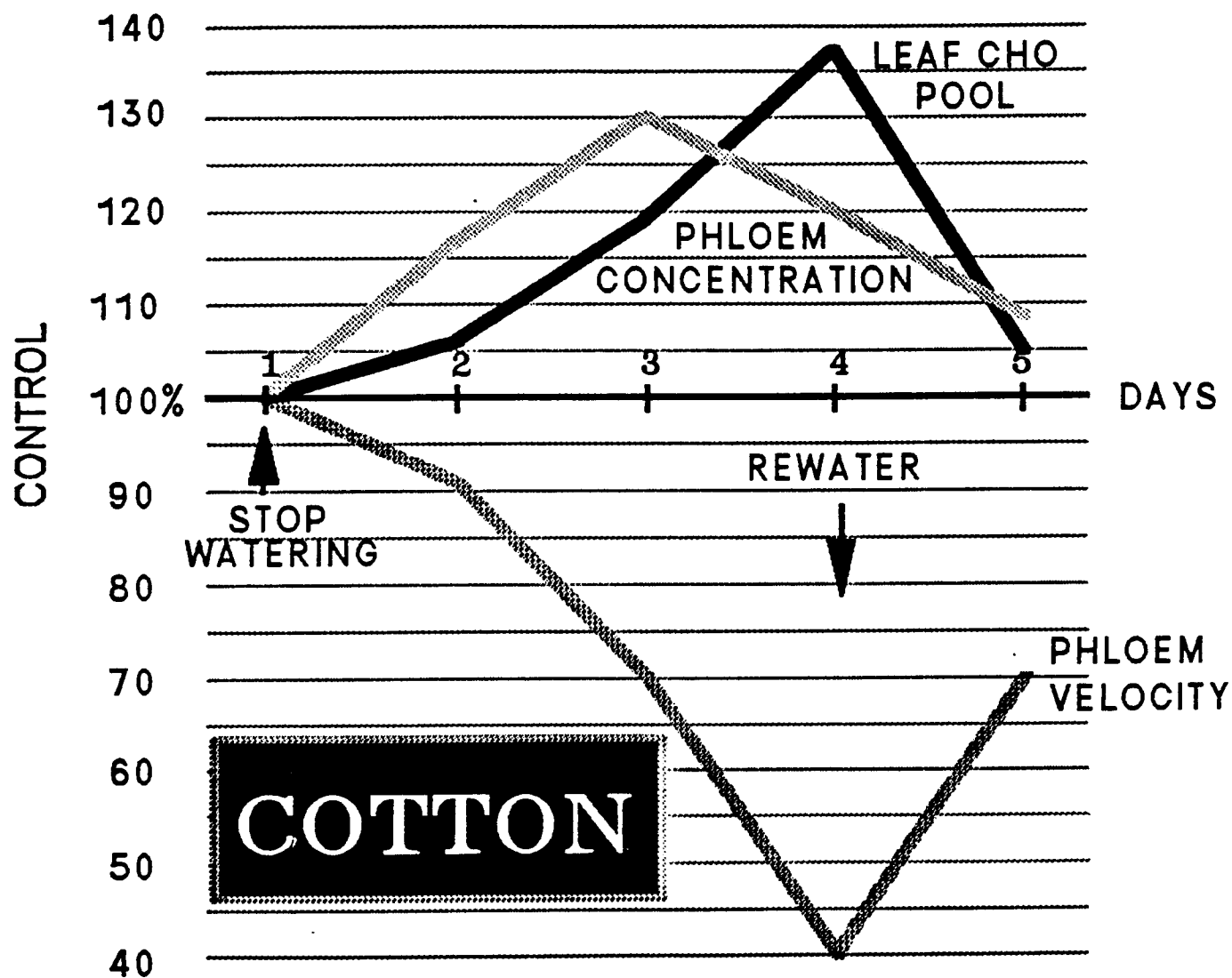


Figure 11. Effect of water stress on carbon transport rate and tissue sugar concentrations in leaf and phloem (transport system).

The plant IRM Model describes how a single plant temperature, relative humidity assimilates carbon dioxide under a given set of conditions for light intensity, carbon dioxide concentration, water and nutrient availabilities. The allocation of the assimilated photosynthate to the above and below ground components of the plant. The water submodel is basically an accounting routine to keep track of water loss through transpiration from the surface, mid and bottom layers of the soil. The nutrient submodel integrates the effects of the various 13 mineral elements required for plant growth.

1. IRM plant growth model.

Figure 8 depicts the integrated effects of the external factors that determine the CO₂ assimilation rate per unit leaf area during a steady-state period.

A set of π_i 's represents the probability of system constituents in various states i during a steady-state period. The quantitative values of π_i 's are determined by the set of external (environmental) controlling factors that influence the mean transition rates of pathways in the network. During a steady-state period, these controlling factors are assumed to be invariant. State 0 (Fig. 8) is considered as the regenerative state. State 1, 2 and 3 are "energized" states, so that when system constituents return to state 0 from these states, excess "energy" can be dumped into the CO₂ assimilation pool. State -1 denotes an energized state that reflects the necessity for plant maintenance and repair. Because this necessary process reduces resources for growth, it is considered as a negative state.

The mean transition rate σ_1 between states 0 and 1 is assumed to be directly proportional to the light intensity I ,

$$\sigma_1 = \beta_1 I \quad (1)$$

where β_1 is the proportionality constant. The transition between states 1 and 0 depicts light respiration, and thus depends on the oxygen concentration $[O_2]$,

$$\sigma_0 = \beta_0 [O_2] \quad (2)$$

The mean transition rate between states 1 and 2 depends on the rate of CO₂ influx through the stomatal pores. An empirical equation developed by Ball *et al.* (1987) is used for the transition in this pathway.

$$\sigma_C = \beta_c g \frac{C_s}{h_s} \quad (3)$$

where C_s and h_s are the CO₂ concentration (in mmol/mol) and relative humidity on the leaf surface, and g is the stomatal conductance in mol m⁻²s⁻¹, which according to Ball *et al.* (1987) is

$$g = 9.31 \frac{A}{C_s} h_s \quad (4)$$

with A being the CO_2 assimilation in $\text{mol m}^{-2}\text{s}^{-1}$.

The transition rates s_H and s_N are functions of soil water (H) and nutrient (N) availabilities, i.e.

$$s_H = f(H) \quad (5)$$

and

$$s_N = f(N) \quad (6)$$

The transition rates between state 0 and -1, s_t and s are proposed to be

$$s_t = f(T) \quad (7)$$

and

$$s = \text{constant} \quad (8)$$

where T is the temperature measured in degree Kelvin. Equation (7) reflects that dark respiration is a temperature dependent process. The detailed functional form of Eq. (7) was published by Sharpe and DeMichele (1977) and Schoolfield *et al.* (1980).

The parallel transition pathways leading from state 1 represent a competition between oxygen and CO_2 molecules for Rubisco (principal Calvin cycle enzyme) in the stomatal leaf tissue. With both gases present at the site (state 1) part of the system constituents undergoes photosynthesis while the remaining part performs photorespiration.

By using the equation of continuity at each state and the normalization condition for probability,

$$\sum_i \pi_i = 1 \quad (9)$$

Thus the fraction of system constituents occupying a state 1, π_1 , can be obtained. The continuity equation for state 1, for instance, can be expressed as

$$s_1 P_0 = (s_O + s_C) P_1 \quad (10)$$

where $s_1 \pi_0$ represents the number of system constituents transferred into state 1 per unit time while $(s_O + s_C) \pi_1$ represents the emigration rate from state 1. There is a total of five such equations, each corresponding to a state. However, one can only use four out of five equations, since one of these is

redundant according to linear algebra theory. Coupling four continuity equations with Eq. (9), one can solve for the five unknowns, π_0 , π_1 , π_2 , π_3 and π_{-1} , from five linear equations in terms of mean transition rates.

The root and shoot pool in Figure 1 represents the assimilated CO_2 per unit leaf area per unit time, i.e.

$$A = \gamma \sigma_N \pi_3 \quad (11)$$

where g is the weighting factor representing the amount of CO_2 assimilation per system constituent. From the expression of π_3 , A can be expressed in terms of mean transition rates,

$$A = \gamma \frac{\sigma_N \sigma_I}{\sigma_I \left[1 + \sigma_C \left(\frac{1}{\sigma_H} + \frac{1}{\sigma_N} \right) \right] + (\sigma_\tau + \sigma_C)} \quad (12)$$

By multiplying the total leaf area LA , the , per unit time photosynthate P can be obtained,

$$P = A * LA \quad (13)$$

total photosynthate P is in turn allocated by the feedback mechanism f to above ground shoots and below ground roots:

$$f = \gamma \frac{\sigma_H \sigma_N}{\sigma_H + \sigma_N + \sigma_I + \sigma_C} \quad (14)$$

The differential equation for the above and below biomass m_\uparrow and m_\downarrow can thus be written

$$\frac{dm_\uparrow}{dt} = \bar{f} * P - \alpha_\uparrow m_\uparrow \sigma\pi - 1 \quad (15)$$

and

$$\frac{dm_\downarrow}{dt} = \bar{f} * P - \alpha_\downarrow m_\downarrow \sigma\pi - 1 \quad (16)$$

where $\bar{f} = 1-f$ and α_\uparrow and α_\downarrow are the weighting factors for biomass loss due to dark respiration. The below ground biomass m_\downarrow can be interpreted as the biomass of roots while the above ground biomass m_\uparrow consists of shoots and leaf biomasses. The total leaf area LA can be updated by

$$L:A=k_1 m_\uparrow \quad (17)$$

where k_1 is a proportionality constant.

2. Soil water availability submodel

Three layers of soil, surface, mid and bottom, are used. Soil water loss per unit area is assumed solely through transpiration TR

$$TR = gW(1-h_s) \quad (18)$$

where $W = 20 - 1.1 T + 0.06 T^2$ is the saturated moisture content, with T being the temperature measured in °C. The water in a given layer j, H_j , can be updated according to

$$H_j = H_j - \frac{TR_j}{(H_j)_{\max}} \quad (19)$$

where $(H_j)_{\max}$ is the field capacity in the jth layer and TR_j is the transpiration water loss from the jth layer. The computation of TR_j depends on the relative root densities and the relative water availabilities among the various layers.

The transition rate σ_H that is controlled by the available water is computed as follows:

$$\sigma_H = \frac{\exp[\gamma_j (H_j - H_j^*)]}{1 + \exp[\gamma_j (H_j - H_j^*)]} \quad (20)$$

and

$$\sigma_H = \max \{ \sigma_H, \epsilon_2 \sigma_H, \epsilon_3 \sigma_H \} \quad (21)$$

where γ_j is the weighting factor for layer j and H_j^* is the characteristic water level at which $sH_j = \frac{1}{2}(\sigma_H)$ max. The parameter ϵ_j in Eq. (21) depends on relative root density in various layers,

$$\epsilon_j = \rho_j / \rho_1 \quad \text{for } j = 2 \text{ and } 3 \quad (22)$$

where ρ_j represents the fraction of roots in layer j. Equation (21) is used for σ_H in Eq. (5).

3. Nutrient availability submodel

In the IRM network for nutrient availability There are 14 states controlled by 13 essential minerals for plant growth. The mean transition rate between states are denoted by σ_x with the subscript x being the controlling mineral or the ph value. The transition pathway between state 13 and the regenerative state 0 is branched by the detrimental effect of sodium. Only the branch that complements the negative effect of sodium can contribute to σ_N in the nutrient availability pool.

The mean transition rate σ_{ph} is given as follows:

$$\sigma_{ph} = \frac{\exp\left(\frac{Ph - Ph_L}{\beta_L}\right)}{\left[1 + \exp\left(\frac{Ph - Ph_L}{\beta_L}\right)\right] \left[1 + \exp\left(\frac{Ph - Ph_H}{\beta_H}\right)\right]} (1 - f_{Al}) \quad (23)$$

where Ph_L and ph_H are low and high threshold Ph values, and β_L and β_H are the respective weighting factor. The factor f_{Al} is a Ph dependent detrimental effect resulting from the soil aluminum content. Other σ_x for x representing various minerals can be expressed as:

$$\sigma_x = \frac{\exp\left(\frac{X - X_L}{\zeta_L}\right)}{\left[1 + \exp\left(\frac{X - X_L}{\zeta_L}\right)\right] \left[1 + \exp\left(\frac{X - X_H}{\zeta_H}\right)\right]} \quad (24)$$

where X_L and X_H are characteristic low and high soil mineral contents for element X, and ζ_{XL} and ζ_{XH} are the respective weighting factors.

The available nutrient σ_N in Eq. (16) can be computed by

$$\sigma_N = \kappa_N f_{Na} \sigma_{13} \pi_{13} = \frac{k_N \bar{N} f_{Na}}{\sum_{l=0}^{13} \sigma_l} \quad (25)$$

where k_N is the weighting factor, $s_0 = sp_H$, and $s_{l>0}$ are the corresponding mineral controls in the IRM network depicted in Figure 2, and $F_{Na} = 1 - f_{Na}$ with

$$f_{Na} = \frac{\exp\left(\frac{N_a - N_a^*}{\zeta_{Na}}\right)}{1 + \exp\left(\frac{N_a - N_a^*}{\zeta_{Na}}\right)} \quad (26)$$

where the meanings of Na^* and ζ_{Na} are similar to the ones given in Eqs. (23) and (24).

4. Simulation procedures

From Eqs. (3), (4), and (12), one can see that the mean transition rate σ_C depends on the CO_2 assimilation A. Thus it is necessary to have a front-end routine for finding the proper starting value for A.

- a. Front-end routine:
 - i. Provide an initial value for A, A*
 - ii. Let A = A*
 - iii. Compute γ by Eq. (4)
 - iv. Compute σ_C by Eq. (3)
 - v. Compute A* by Eq. (12)
 - vi. If $|A^* - A| > 10^{-6}$ return to step ii, otherwise use the value A for simulation run
- b. Main routine - SIMULATION RUN
 - i. Compute γ by Eq. (4).
 - ii. Compute σ_C by Eq. (3)
 - iii. Obtain σ_H from subroutine WATER.
 - iv. Obtain σ_N from Eq. (25).
 - v. Compute A from Eq. (12)
 - vi. Compute the above-ground biomass by Eq. (15).
 - vii. Compute the below-ground biomass by Eq. (16).
 - viii. Compute the per unit area transpiration by Eq. (18).
 - ix. Update the available water in various layers in subroutine WATER
 - x. Return to step i. for next iteration.
- c. Subroutine WATER
 - i. If $\sigma_{H2} < 10^{-3}$ call subroutine WATER3.
 - ii. If $\sigma_{H1} < 10^{-3}$ call subroutine WATER2.
 - III. Call subroutine WATER1.
- d. Subroutine WATER1

$$H1 = H1 \frac{TR}{(H1)_{\max} \exp[\gamma_1(H1 - H1^*)]}$$
 - i.
 - ii. $\sigma_{H1} = \frac{1}{1 + \exp[\gamma_1(H1 - H1^*)]}$
 - iii. call routine WATER2
- e. Subroutine WATER2
 - i. If $(\sigma_{H1} > 0.999)$ or $(\sigma_{H2} < 0.999)$ Go to step V.
 - ii.
$$A = \gamma \frac{\sigma_C \sigma_I}{\sigma_I \left[1 + \sigma_C \left(\frac{1}{\sigma_{H2}} + \frac{1}{\sigma_N} \right) \right] + (\sigma + \sigma_\tau)(\sigma_0 + \sigma_C)}$$
 - iii.
$$g = 9.31 \frac{Ah_s}{C_s}$$

iv. $Tr = gW (1-h_s)$

v. $H_2 = H_2 \frac{TR}{(H_2)_{\max}}$

vi. $\sigma_{H_3} = \frac{\exp[\gamma_3 (H_3 - H_3^*)]}{1 + \exp[\gamma_3 (H_3 - H_3^*)]}$

vii. $\sigma_H = \max \{ \sigma_{H_1}, \xi_2 \sigma_{H_2}, \xi_3 \sigma_{H_3} \}$

viii. Return to the main routine SIMULATION RUN

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SECTION III
INTERDISCIPLINARY RESEARCH

Chapter 7

**CONTROL OF CO₂ CONCENTRATION
THROUGH TEMPERATURE EFFECTS ON
PLANT GROWTH**

Prepared by

A. Garcia III

B. Wright

Agricultural Engineeirng

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Chapter 7

CONTROL OF CO₂ CONCENTRATION THROUGH TEMPERATURE EFFECTS ON PLANT GROWTH

INTRODUCTION

Modeling and simulation are important techniques in the design of a Controlled Environment Life Support System (CELSS). Through simulation we can estimate the state of the system under a given set of conditions. Unfortunately, our knowledge of plant physiology is unquestionably incomplete. There are many plant responses to the environment we do not understand. The biology of plants tends to be very plastic and adaptable. The past history of the plants' environment will determine how the plants react to a new stimulus. We cannot model much of this adaptive ability because the information about it does not exist or is incomplete. Thus, obtaining a good estimation of the system through modeling may be difficult to presently achieve.

This poses a problem for control of a CELSS. Knowing how a CELSS will react to a given set of conditions is important for setting up a schedule of events in the maintenance and operation of a CELSS. We propose to investigate if the same adaptability and plasticity that causes problems for modeling can be utilized to develop a simple and effective control and planning strategy for CELSS operation.

OBJECTIVES

1. Verification that the response of plant photosynthesis to CO₂ concentration can be used for control of CO₂ in a closed life support system. We assume direct interaction between the plants and the crew with no mechanical or chemical buffer between them. Temperature will be used to adjust the rate processes in the plants and, therefore, adjust the mean and standard deviation of the CO₂ concentration.
2. Design of a control system which utilizes aspects of cognitive planning techniques and artificial intelligence to select the proper set of environmental conditions which will ensure adequate CO₂ control and maintain an acceptable yield potential for the plants.

DISCUSSION

We hope to demonstrate, through the two objectives listed above, that the concept of a biological life support system can be simplified by utilizing the physiology of the biological components. Mechanical and chemical buffers between the crew and the biological systems can be reduced or eliminated resulting in a whole system which has fewer mechanical components and, hopefully, is less expensive to develop and maintain. The control of CO₂ in the atmosphere was chosen as a case study.

A pilot study was conducted utilizing a stochastic simulation shown graphically in Figure 7.1. There are two separate modules with air being continuously exchanged between them. One module contains four crew members with randomly varying rates of CO₂ given off from each person. The other module contains two sets of plants which remove the CO₂ produced by the crew. One set of plants is in the light while the other set is in the dark. Every twelve hours the lighting is reversed. The model is discussed in detail in the appendix. This model allows the variation of many parameters and an analysis of variance was conducted on many of the parameters. For this proposal the discussion is limited to the effect of temperature variation of the plants on the CO₂ concentration in the system.

Temperature affects the rates of photosynthesis and respiration in plants. The rates increase as temperature is increased until maximum rates are reached. Increasing the temperature beyond this point will cause the rates to decrease. This temperature response curve varies with plant species since plants are adapted to various climates. Plants also have the ability to acclimate to temperatures, thus, the temperature response curve not only depends upon the species adaptation to a given climate, but also the temperatures in which the plant has been grown locally (Badger, M. R. *et al*, 1982). For instance, a plant grown at a constant 35 °C will have a given temperature response curve. If the the temperature is changed to a constant 30 °C, photosynthesis and respiration rates will decrease. However, over a period of several days, the plant will acclimate to this new temperature and the photosynthesis and respiration will increase. The plant will have a new temperature response curve.

Temperature adaptation and acclimation are just one example of the plastic behavior of biological components in a CELSS that will make modeling for control very difficult. Since the understanding of plant physiology is incomplete, we can, using an intelligent control system, approach the problem from a different perspective.

[An intelligent] agent is perpetually engaged in an infinite loop of perceiving things, reasoning about them, and taking actions. The actions are determined by a set of internal beliefs, goals, and objectives in interaction with what is perceived. A major task for such an agent is to acquire a model of the world in which it is embedded and to keep its model sufficiently consistent with the real world that it can achieve its goals. Knowledge of the world consists of two kinds of things—facts about what is

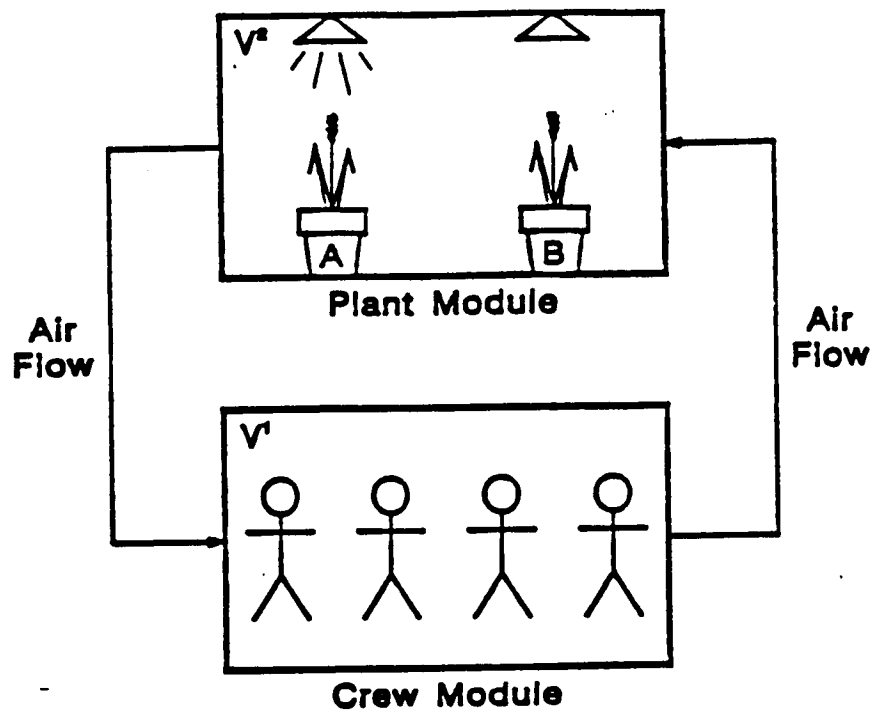


Figure 7.1. The model used to study the CO₂ balance in a closed system with plants and crew.

or has been true (the known world state) and rules for predicting changes over time, consequences of actions, and unobserved things that can be deduced from other observations (the generalized physics/logic/psychophysics/sociology of the world) (Woods, A. W., 1986).

The approach to controlling CO₂ consists of observing the environment and deducing the state of the plants. Changes in the environment, if needed to reach a desired state, are achieved by a knowledge based control system which contains a model of plant physiology 'sufficiently consistent with the real world that it can achieve its goals.' The goal is not to accurately predict plant behavior so that we can control the system. The goal is, simply, to control the system and maintain the health of the plants. In fact, a strategy for achieving this goal is to allow the plants themselves to control the CO₂ by utilizing a natural feedback response in the plants to CO₂ concentration. This response is augmented through the use of temperature.

Figure 7.2 shows the mean CO₂ concentration in the plant and crew modules when the plants in the model are exposed to various temperatures. The crew output of CO₂ randomly varies with time and so the CO₂ concentration in the atmosphere will also randomly vary. The standard deviation of the CO₂ concentration in the atmosphere of the modules is shown in Figure 7.3 for various plant temperatures. It is important to note that the standard deviation of the CO₂ concentration decreases as the mean CO₂ concentration decreases. Understanding the reason for this phenomenon is the key to utilizing the plants for CO₂ control.

The rate of photosynthesis will increase as CO₂ concentration is increased. However, this effect becomes less and less significant as the concentrations increase until further increases in CO₂ concentration have very little benefit. This response curve is temperature dependent. Figure 7.4 shows two such curves from the simulation, one for 25 °C and the other for 29 °C. When the plants are at 25 °C the mean CO₂ concentration is high and the plants are operating on a relatively flat section of the photosynthesis versus CO₂ concentration curve. It takes large changes in the CO₂ concentration to affect small changes in the photosynthetic rate. However, if the temperature is increased to 29 °C, the mean photosynthetic rate is slightly increased by ΔP and the mean CO₂ concentration is decreased. The plants are now operating on a steep section of the photosynthesis versus CO₂ concentration curve. The response of photosynthesis to changes in CO₂ is more dramatic. Changes in the CO₂ output of the crew are quickly compensated for by the plants when they are operating in this range. Thus, a major factor in achieving our goal to maintain the CO₂ concentration within a certain range is to keep the operating point of the plants on the steep section of the curve.

We can get an idea of the position of the operating point on the photosynthesis versus CO₂ concentration curve by defining a parameter called the *relative variance*, σ_{rel}^2 , of the

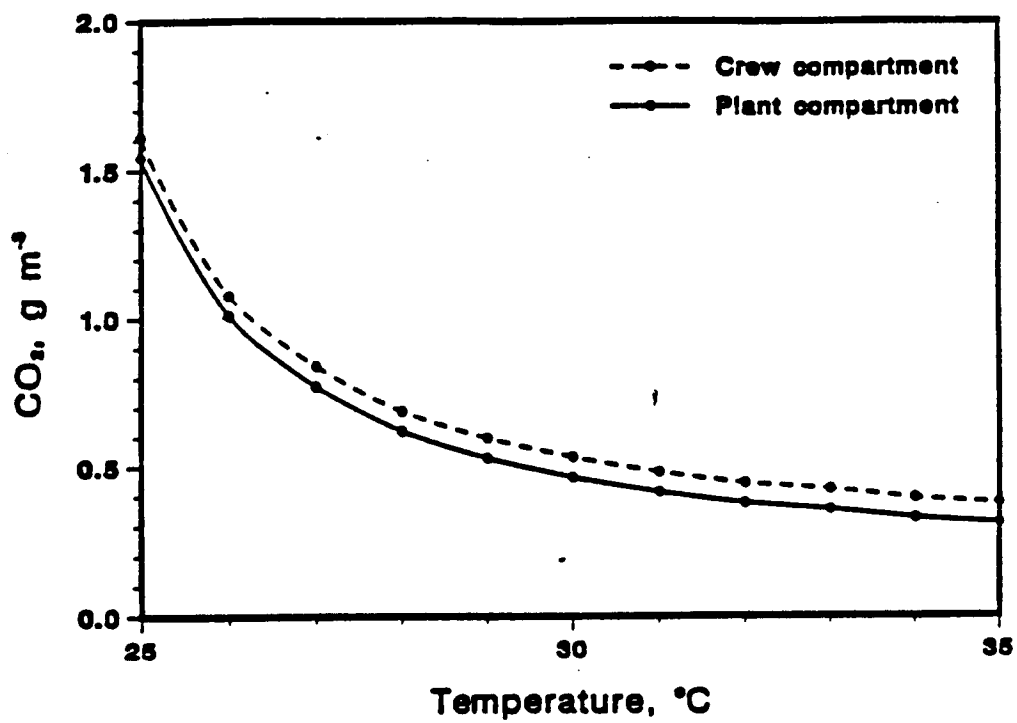


Figure 7.2. The mean CO₂ concentration of the system for various plant temperatures.

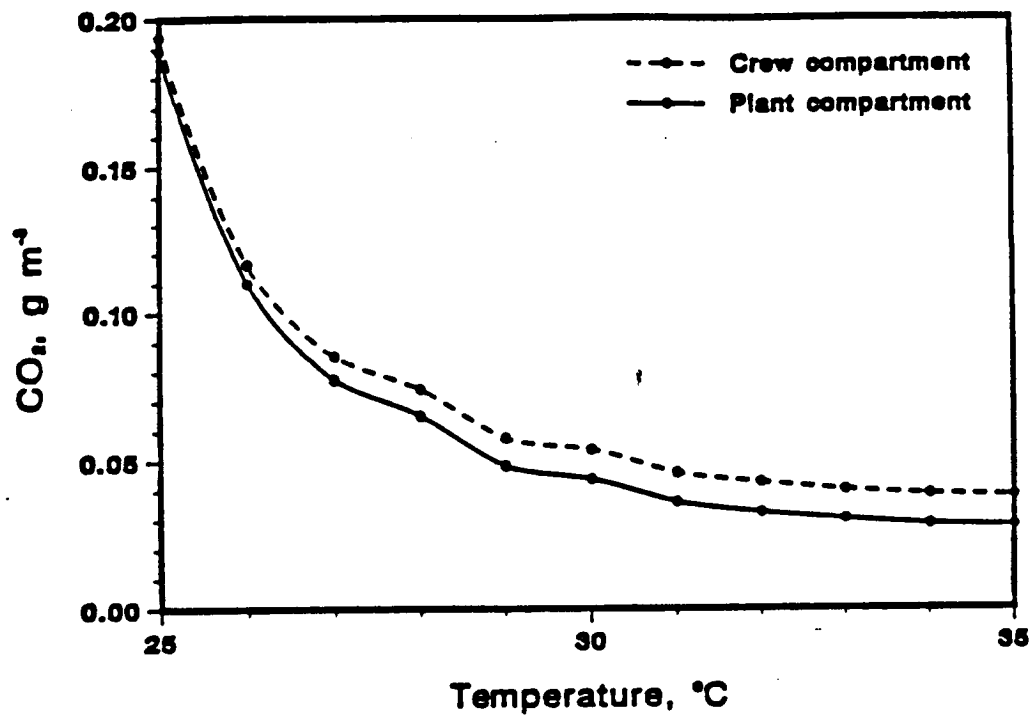


Figure 7.3. The standard deviation of the CO₂ concentration of the system for various plant temperatures. The waviness of the line is due to random factors in the model.

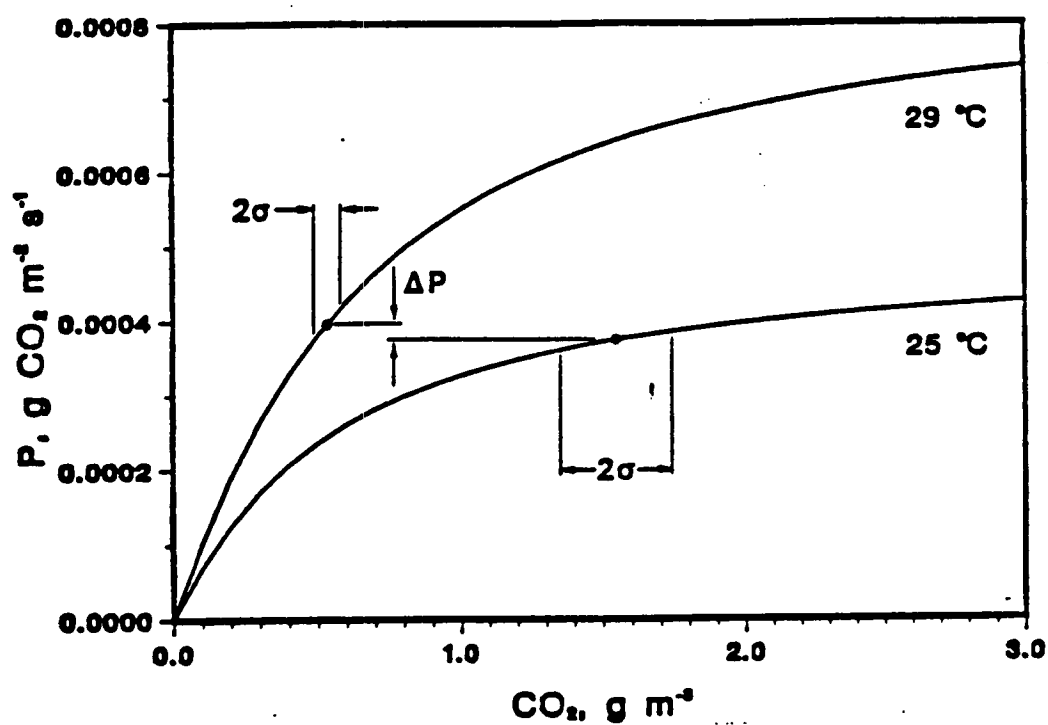


Figure 7.4. Photosynthesis versus carbon dioxide concentration at two temperatures. The dots on the lines represent the operating point for a mean CO_2 concentration in a simulation at that temperature, σ is the standard deviation of CO_2 and ΔP is the change in photosynthesis rate when the temperature is changed.

CO₂ concentration.

$$\sigma_{rel}^2 = \left(\frac{\sigma_p}{\sigma_c} \right)^2$$

The terms σ_p and σ_c are the standard deviations of the CO₂ concentrations in the plant and crew modules respectively. The value from the simulation for the 25 °C case σ_{rel}^2 is 0.95 and for the 29 °C case σ_{rel}^2 is 0.70. Thus, σ_{rel}^2 can be said to be a measure of the control the plants are exerting on the CO₂ concentration. When σ_{rel}^2 approaches the value of 1.0, control is poor and environmental adjustments must be made to lower σ_{rel}^2 to a value that indicates the plants are operating on the steep section of the the photosynthesis versus CO₂ curve. If the plants are operating on the flat portion of the curve the system can easily become unstable.

The second performance index we can use is the absolute concentration of the CO₂. Values too high or too low can be detrimental to plant growth. If the CO₂ concentration is too low, then photosynthetic production of carbohydrates will be reduced. The limited amount of carbohydrates produced will be used mostly by maintenance respiration in the plants and little growth will occur. If the CO₂ levels are too high, damage such as chlorosis or leaf roll may occur (van Berkel, N., 1984) and photosynthetic efficiency may be reduced (Kreidemann, P.E. and S.C. Wong, 1984, Delucia, E.H. et al, 1985) although these affects appear to vary with species. Cooling or warming the plants will allow adjustment of the mean absolute CO₂ concentration.

The short-term control of a CELSS will depend greatly upon the long-term goals of the system. For instance, suppose an increase in the size of the crew is scheduled. The total leaf area of the plants in the CELSS will need to be increased in anticipation of the expected increase in crew CO₂ output, thus, additional planting area is seeded. As the new plants grow and leaf area increases the temperature of the system will have to be decreased to keep the CO₂ demand by the plants matched to the present crew size. When the additional crew members arrive the temperature can be increased to meet the increase in CO₂ output.

There are three parameters which provide a spectrum of time responses for CO₂ control. Changes in light intensity will provide an immediate response in CO₂ concentration since photosynthesis will respond immediately. Changes in temperature will provide a response in the range of minutes to hours depending upon the time it takes to cool or heat the mass in the system. Changes in leaf area will provide a response in the range of hours for the decrease in leaf area (harvest) or days for an increase in leaf area (growth). All three of these parameters must be accounted for at all times.

Planning and control of the system cannot be separated in this case. Anticipation of future system events affects short-term control and the short-term system response will affect long term adjustments needed to meet those same goals. Cognitive planning techniques (Hayes-

Roth, B. and F. Hayes-Roth, 1979) and blackboard systems (Nii, P., 1986a, Nii, P., 1986b) can be used. In these techniques planning occurs on several levels, Figure 7.5. Local 'experts' interact with a database called the 'blackboard'. Each expert affects the plan at a different level of abstraction based upon what is read from the blackboard and changes the blackboard accordingly. The most abstract level determines what the long-term plan is intended to accomplish. The next lower level would provide a general approach to achieve the desired outcomes. Lower levels provide greater refinement to the plan until at the lowest level the environment is being altered and measured. All of these experts interact through the blackboard rather than through direct expert-to-expert interaction. Lower levels can affect and cause changes at higher levels. An executive guides and directs the planning process.

There will be constraints on the system such as power, plant growth rates, or cropping rotations to meet nutritional demands. Planning under constraints (Stefik, M., 1981) can be utilized to allocate limited system resources or meet a given set of restrictions. This may require negotiation and compromise with systems outside of the CELSS.

The biological components in the CELSS cause uncertainty in expected outcomes from the executed plan. Stochastic simulations can be used to predict the outcomes of a selected plan and Dempster-Shafer Theory (Zadeh, L.A., 1986) or statistical methods for decision making heuristics (Spiegelhalter, D.J., 1986, Fox, J., 1986) can provide a measure of the uncertainty in the outcomes of stochastic simulations of the CELSS and assist in making changes in the plan at more abstract plan levels if it appears that goals will not be met. Planning decisions can also be based upon lookup tables generated by past experience and procedures (Georgeff, M.P. and A.L. Lansky, 1986) and plans can be pieced together based upon previous successes.

Most of this discussion about planning and control in a CELSS is, clearly, beyond the scope of this project. It is important, however, to have a view of the whole in order to understand how the pieces fit together. This work would involve the lowest, least abstract level, that is, immediate control of the plant environment, yet, there must be some recognizable goal in order to determine what that environment should be. We should be able to adjust the CO₂ level and rate of plant development to meet a desired abstract goal through the use of temperature control. This will be accomplished by utilizing σ_{rel}^2 and the absolute CO₂ concentration in conjunction with a knowledge based system containing a model of plant growth. A detailed plant growth model is not needed for this purpose. All we need is knowledge about cause and effect and the range of response we can expect from the plants. We will generate the goals manually, (i.e., increase leaf area and maintain a constant mean CO₂ demand by the plants) and allow the temperature 'expert' to exercise control of the system.

Modeling of a CELSS can be useful for an understanding of the system, but our present knowledge of plant physiology is inadequate. There are many plant processes we simply do

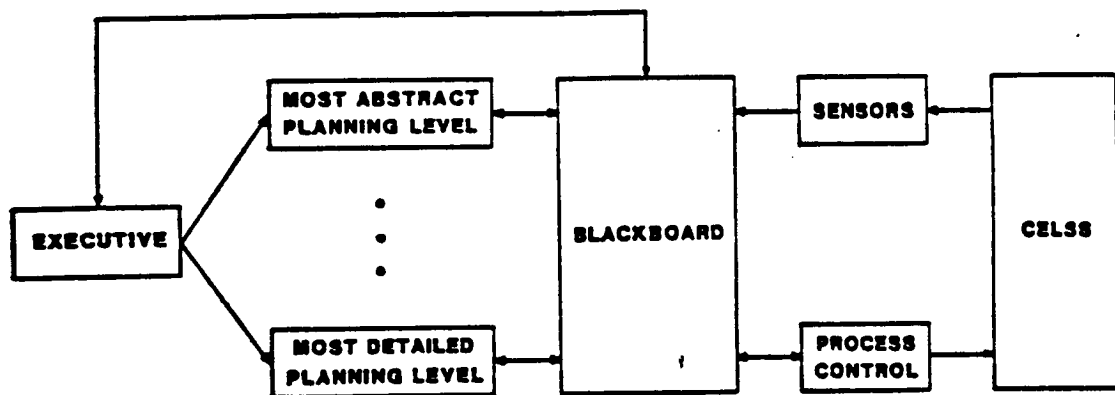


Figure 7.5. A model of planning and control using levels of plan abstraction and a blackboard system for communication.

not understand. Of those which are fairly well known, an attempt to achieve accuracy results in an explosion in the number of coefficients and equations used. The amount of work needed to obtain all of the values required for an accurate, detailed CELSS analysis will take years of work. The artificial intelligence techniques mentioned above may provide a solution which avoids the complexity of attempting to completely model plant growth in order to plan and control a CELSS. We try, simply, to get close enough to get the job done. Modeling should continue, but the field of CELSS design must attempt to achieve results with the knowledge and tools which are presently available.

PROJECT REQUIREMENTS

All experiments will be conducted in a small scaled dual growth chamber as shown in Figure 7.6. This will allow the simulation of two sets of plants which alternate their day/night cycles. This chamber should be air tight. Since a chamber of this design does not exist at Texas A&M, the first phase of this project will be its construction. The air will circulate between the two chambers quickly to maintain as much similarity between their environments as possible. This dual plant growth chamber represents the plant module in a CELSS. The crew module is simulated. The input/output air flow stream for the system is once-through so that control of the O₂ in the system does not need to be implemented. The CO₂ concentration of the output will be monitored. The input CO₂ concentration will reflect the effect of recycling the air flow through a crew module. The crew respiration will be simulated and the CO₂ in the input stream adjusted accordingly. An interface system will provide data collection and processing services for the knowledge based system running on a personal computer. An infrared gas analyzer will be used to measure the absolute CO₂ concentration in the chamber and the differential CO₂ concentration of the input and output gas streams of the plant growth chamber. This information will provide the values for σ_{rel}^2 and the absolute CO₂ concentration needed for control and planning.

After completion of the chamber construction we will determine the net photosynthesis versus CO₂ concentration curve for wheat plants at various temperatures. We will then test the feasibility of using the parameter σ_{rel}^2 . This will be accomplished by imposing an input signal of CO₂ concentration on the input flow of the system and measuring the output concentration. The input signal will have an 'ac' component and a 'dc' component. Variation of these two components should provide the information needed to test the efficacy of σ_{rel}^2 as a control parameter.

The final phase of the project is testing the 'temperature expert' for its ability to adjust the temperature and maintain σ_{rel}^2 within a given range of values and maintain the absolute CO₂ concentration within a given range of values.

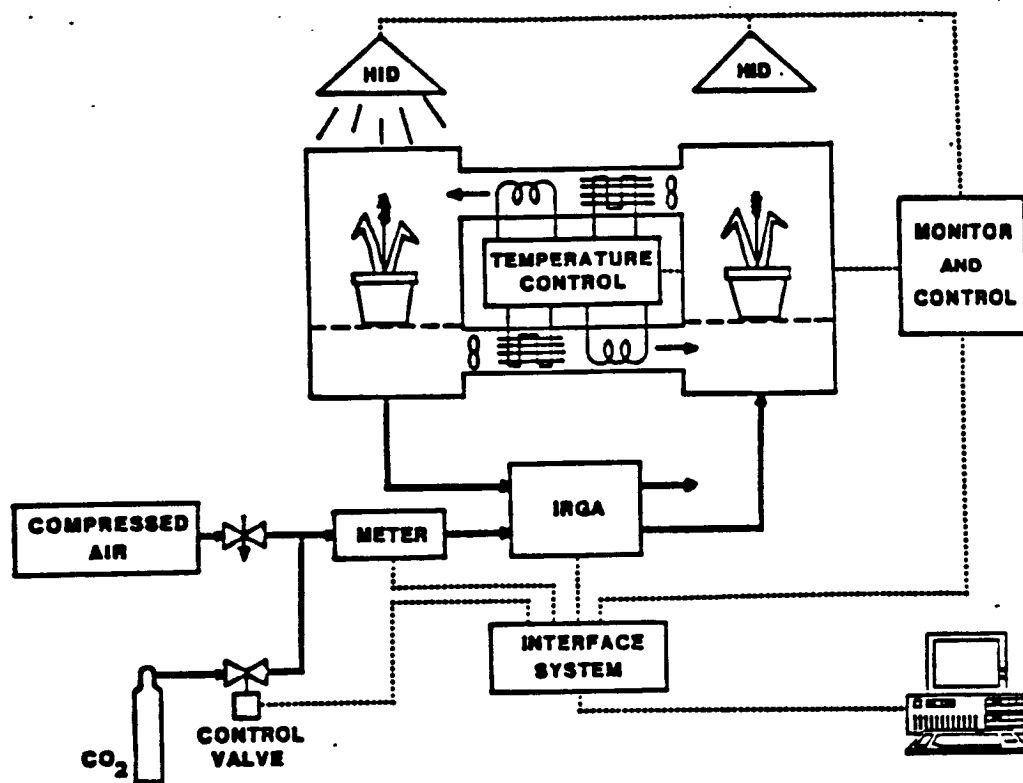


Figure 7. .6 Dual plant growth chamber, air flow monitoring and CO₂ control.

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CREW MODEL

The crew is composed of four people. Carbon dioxide output of the crew is a function of activity level and food composition. The assumption is made that crew activity level will range between sleeping and moderate activity such as cycling. The energy needed to carry out these tasks (Webb, 1973) varies from 77 Watts to 420 Watts. One crew member is asleep at all times with the others varying their activity levels uniformly between 84 Watts and 420 Watts. The activities change randomly from 15 minutes to 1 hour using a uniform distribution.

Table 7.A.1. Crew activity distributions.

Crew member	Activity level, Watts
1	UNIFORM(77, 90) <i>Sleeping</i>
2	UNIFORM(84, 420) <i>Active</i>
3	UNIFORM(84, 420) <i>Active</i>
4	UNIFORM(84, 420) <i>Active</i>

The proportion of carbohydrate, fat and protein in the food will affect the carbon dioxide given off by the crew in order to obtain the energy needed for their prescribed activity levels. The food composition (Tibbits and Alford, 1982) was determined as shown in Table 2 and changed every 12 hours. The 12 hour period was used to emulate the 'averaging' affect of the intestinal system.

Table 7.A.2. Proportions of protein, fat and carbohydrate in food.

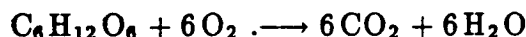
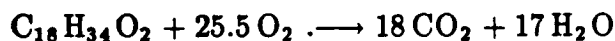
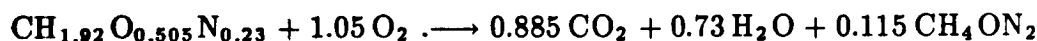
Food Item	Proportion in food
Protein	NORMAL(.214, .09)
Fat	NORMAL(.062, .04)
Carbohydrate	1 - Protein - Fat

The energy available per gram of food is used to determine the rate of food oxidation by the crew (Holzapple, 1987).

$$\frac{\text{J}}{\text{g Food}} = \left(\frac{\text{g Protein}}{\text{g Food}} \right) \left(\frac{22626 \text{ J}}{\text{g Protein}} \right) + \left(\frac{\text{g Fat}}{\text{g Food}} \right) \left(\frac{39389 \text{ J}}{\text{g Fat}} \right) + \left(\frac{\text{g Carbohydrate}}{\text{g Food}} \right) \left(\frac{16760 \text{ J}}{\text{g Carbohydrate}} \right)$$

$$\frac{\text{g Food}}{\text{sec}} = \frac{\text{Watts of Crew Activity}}{\text{J/g Food}}$$

The stoichiometry for the oxidation of protein, fat and carbohydrate consumed by the crew is used to calculate the carbon dioxide production of the crew. The stoichiometry is given for protein (casein), fat (oleic acid) and carbohydrate respectively.



$$\text{R}_{\text{crew}} = \left(\frac{\text{g Protein}}{\text{g Food}} \right) \left(\frac{1.544 \text{ g CO}_2}{\text{g Protein}} \right) + \left(\frac{\text{g Fat}}{\text{g Food}} \right) \left(\frac{2.809 \text{ g CO}_2}{\text{g Fat}} \right) + \left(\frac{\text{g Carbohydrate}}{\text{g Food}} \right) \left(\frac{1.467 \text{ g CO}_2}{\text{g Carbohydrate}} \right)$$

PLANT MODEL

The plant model selected for this simulation was developed for studying the flow of carbon in the plant between various sinks (McCree, 1982). Photosynthesis, P , puts carbon into the plant in the form of soluble sugars, W_{SO} . Some of the sugars are converted to starch, W_{ST} . Starch production is a light sensitive process. The velocity of the reaction is reduced in the dark. Also, starch is converted back into sugars. This process is not light sensitive and continues at the same velocity day or night. Respiration converts sugars into degradable biomass, W_D , and non-degradable biomass, W_N , and some of the carbon is returned to the atmosphere as carbon dioxide. The degradable biomass can be converted back into sugars. The model coefficients (McCree and Amthor, 1982) were obtained from work on white clover. The following differential equations describe the flux of carbon into and out of each sink. There is a set of equations for each group of plants, A and B.

$$\frac{dW_{SO}}{dt} = P - \frac{V_{ST}W_{SO}}{K_{ST} + W_{SO}} + \frac{V_{SO}W_{ST}}{K_{SO} + W_{ST}} - k_G W_{SO} + k_D W_D \quad (1)$$

$$\frac{dW_{ST}}{dt} = \frac{V_{ST}W_{SO}}{K_{ST} + W_{SO}} - \frac{V_{SO}W_{ST}}{K_{SO} + W_{ST}} \quad (2)$$

$$\frac{dW_D}{dt} = Y_D Y_G k_G W_{SO} - k_D W_D \quad (3)$$

$$\frac{dW_N}{dt} = (1 - Y_D) Y_G k_G W_{SO} - k_D W_D \quad (4)$$

$$R_{plant} = (1 - Y_G) k_G W_{SO} \quad (5)$$

The photosynthesis model (Campbell, 1977) is a function of carbon dioxide concentration in the atmosphere, light intensity and temperature. Photosynthesis, P , is affected by the resistance to carbon dioxide diffusion from the air to the chloroplast, r_c , the ambient carbon dioxide concentration, ρ_{ca} , and the concentration at the chloroplast, ρ_{cc} .

$$P = \frac{\rho_{ca} - \rho_{cc}}{r_c} \quad (6)$$

The value of r_c is affected by the plant stomates. The opening and closing of the stomates has been shown to be affected by the concentration of CO_2 in the ambient air (Morison, I.L., 1987). The sensitivity of the response varies with species. We assumed complete insensitivity of the stomates to CO_2 concentration in this simulation. The effect of ρ_{cc} on photosynthesis is approximated by a Michaelis-Menton-type equation where P_M is the rate of photosynthesis at CO_2 saturation and K is a rate constant.

$$P = \frac{P_M \rho_{cc}}{K + \rho_{cc}} \quad (7)$$

Combining equations 6 and 7 gives us an expression for P .

$$P = \frac{(\rho_{ca} + K + r_c P_M)}{2 r_c} - \frac{\sqrt{(\rho_{ca} + K + r_c P_M)^2 - 4 \rho_{ca} r_c P_M}}{2 r_c} \quad (8)$$

The value of P_M will depend upon leaf temperature and the flux density of photosynthetically active radiation, PAR,

$$P_M = \frac{P_{MLT} T_P PAR}{K_L + PAR} \quad (9)$$

where P_{MLT} is the maximum photosynthesis at light saturation and optimum temperature and K_L is the rate constant for light. The temperature function, T_P , is based upon the Arrhenius relationship and enzyme kinetics (Schoolfield, *et al*, 1981, Sharpe, 1983).

$$T_P = \frac{1}{1 + e^{\left[\frac{\Delta H_L}{R} \left(\frac{1}{T_{1/2L}} - \frac{1}{T}\right)\right]} + e^{\left[\frac{\Delta H_H}{R} \left(\frac{1}{T_{1/2H}} - \frac{1}{T}\right)\right]}} \quad (10)$$

The parameters $T_{1/2L}$ and $T_{1/2H}$ represent the low and high temperatures at which the process is one-half inactive and ΔH is the enthalpy of activation of the enzyme.

There are two sets of plants, A and B. Each set goes through a complete day/night cycle. While one set of plants is illuminated the other set is in darkness. This arrangement insures that photosynthesis is always removing carbon dioxide from the atmosphere. The plants in group A begin in the light and group B is in dark. The net carbon dioxide uptake is positive for the plants in the light and carbon dioxide is given off by plants in the dark. Every twelve hours their roles are reversed.

The final step in the model is to make a mass balance of the CO_2 in each chamber since CO_2 is the gas whose concentration depends solely on the biological reactions of the plants and crew. All plant parameters were calculated on a square meter basis. Calculations involving total gas exchange between the plants and the atmosphere were scaled up using the leaf area, LA, of each set of plants.

$$\frac{d\text{CO}_2^1}{dt} = \left(\frac{\text{CO}_2^2}{V^2} - \frac{\text{CO}_2^1}{V^1}\right) Q + R_{\text{crew}}$$

$$\frac{d\text{CO}_2^2}{dt} = \left(\frac{\text{CO}_2^1}{V^1} - \frac{\text{CO}_2^2}{V^2}\right) Q + \text{LA}^A (R_{\text{plant}}^A - P^A) + \text{LA}^B (R_{\text{plant}}^B - P^B)$$

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 8

ARTIFICIAL CHLOROPLAST

Prepared by

**F. VanDuker
M. Holtzapple
Chemical Engineering**

Chapter 8

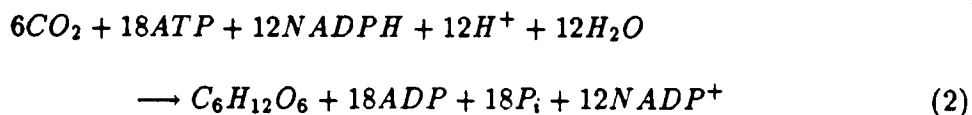
ARTIFICIAL CHLOROPLAST

INTRODUCTION

The goal of this research is to develop a regenerative life support system which is required for extended missions in space. The respiration of an astronaut may be represented as



where $C_6H_{12}O_6$ is glucose, a carbohydrate food source. To produce the glucose, the reverse of the above reaction must occur. The natural photosynthetic process uses light energy to fix the carbon dioxide as glucose. This process occurs in two phases: one requires light and the other does not. The phase which does not require light is the Calvin Cycle which converts carbon dioxide to glucose by a series of 15 reaction steps which sum to the following overall reaction(Lehninger, A.L., 1975):



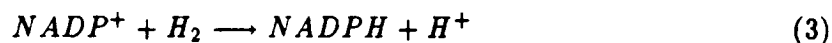
Fortunately, the Calvin Cycle has been studied since the 1950's, so this cycle is well understood. The reaction requires twelve enzymes and thirteen intermediates and occurs in the stroma of chloroplasts (Lehninger, A.L., 1975). The affinity constant (K_m) of the enzymes for substrates is known for virtually every enzyme. The enzymes function best around pH 8 (Edwards, G. *et al*, 1983). Also, the enzymes are in solution which makes them simple to use.

In nature, the energy required by the Calvin Cycle is supplied by light which is used to regenerate adenosine triphosphate (ATP) and reduced nicotinamide adenine dinucleotide phosphate(NADPH). For space applications, it is desirable to eliminate light driven reactions since the production of light from electricity is inefficient and it may be possible to use electricity directly to power the fixation of carbon dioxide as glucose. The artificial chloroplast will accomplish this goal.

Figure 8.1 shows a schematic of the proposed system. The astronaut eats glucose, breathes oxygen, and exhales carbon dioxide and water. The water is condensed from the air and is electrolyzed to produce the oxygen required for breathing. Additional water may be obtained from processing urine and other water wastes. The power source for the electrolysis unit can be envisioned as a nuclear-powered Stirling engine.

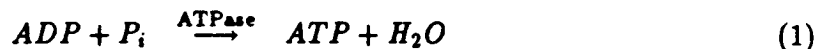
The dehumidified air is then stripped of carbon dioxide. Trace amounts of oxygen which may accompany the carbon dioxide will be removed in a catalytic combustor by reacting it with hydrogen produced in the electrolysis unit. This step is required since some of the enzymes are oxygen sensitive. Purified carbon dioxide is introduced into the Calvin Cycle reaction vessel where glucose is enzymatically produced. The glucose is removed from the reaction mixture by a membrane which passes small, uncharged molecules. Since all other species are charged or are of high molecular weight, this separation should be possible.

The NADPH required by the dark reaction is regenerated according to the following reaction (Wong, C-H, 1981)



using hydrogen dehydrogenase (E.C.1.12.1.2).

Since the Calvin Cycle is fairly well understood and NADPH regeneration has been demonstrated, the major technical barrier of this system is the regeneration of ATP. ATP molecules are synthesized naturally in the plasma membranes of bacteria and in the inner membranes of mitochondria and chloroplasts by a process known as chemiosmosis. Chemiosmotic ATP synthesis, first proposed by Peter Mitchell in 1961, requires two steps. In the first step, electrons (e^-) and protons (H^+) of hydrogen atoms are separated with a concentration of H^+ on one side of the membrane, thus, creating an electrochemical gradient called the protonmotive force (p.m.f.). In the second step, this build up of energy is used to power the phosphorylation of ADP



which is an endergonic reaction.

Therefore, both a chemical potential gradient ΔpH as well as an electric potential difference $\Delta\varphi$ is required to synthesize ATP from ADP and P_i in nature. These gradients are vectorial, not scalar. Thus, the enzyme must be properly oriented with respect to the

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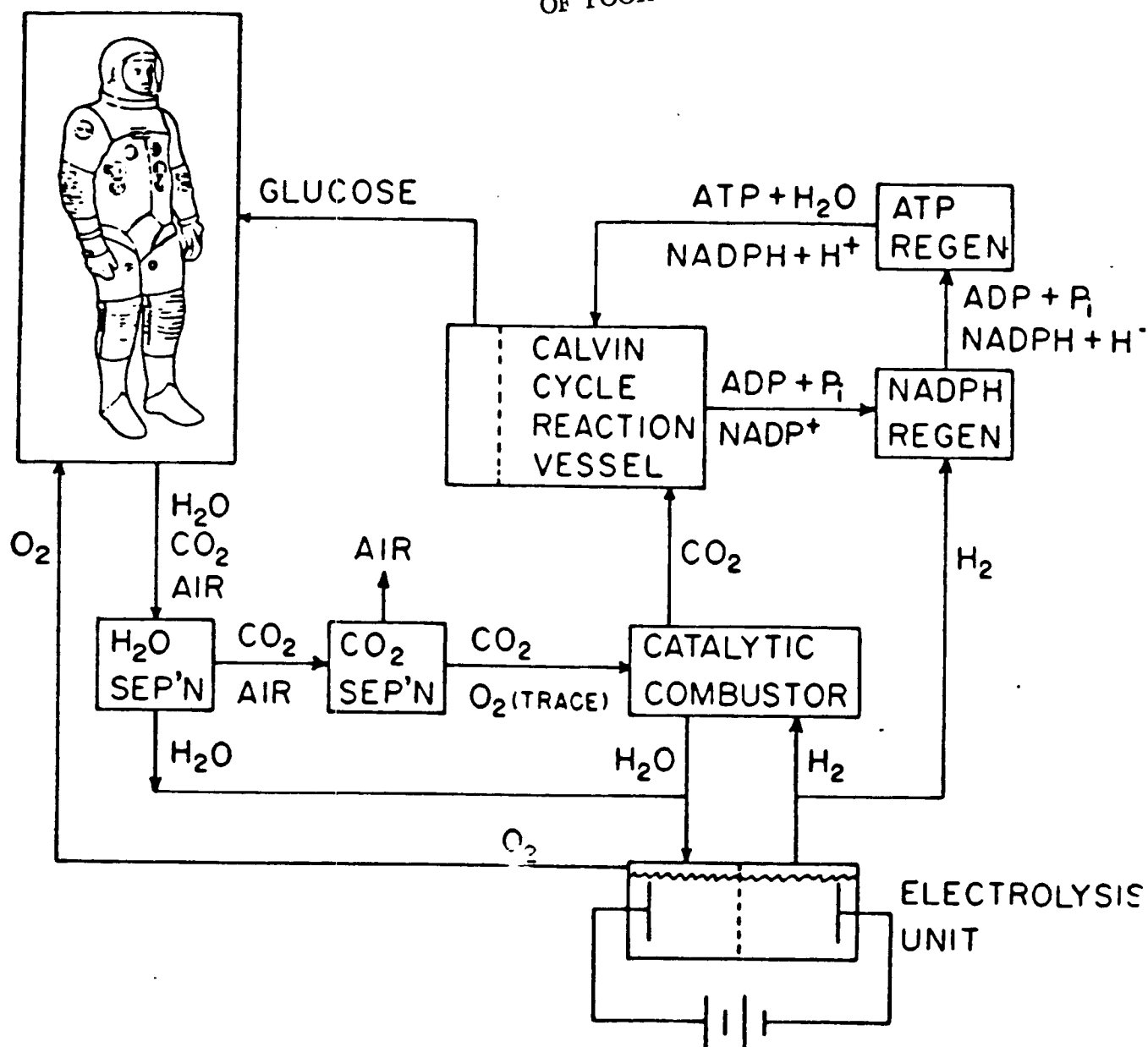


Figure 8.1. Overall flow scheme.

gradient in order to function. This orientation is accomplished by mounting the enzyme in a membrane (see Figure 8.2). The F_0 subunit of ATPase is embedded in the membrane and provides a passageway for electrons to flow. The F_1 subunit is catalytically active and provides the site for the phosphorylation of ADP.

There is increasing evidence that the p.m.f. required to phosphorylate ADP is due to the addition of the free energy, ΔG , stored in the ΔpH and the ΔG stored in the $\Delta\varphi$ and that the energy may come from one or the other if artificially induced. It is known that 7.3 kcal/gmole of free energy is required to synthesize ATP from ADP at standard conditions. If the p.m.f. is a result of a ΔpH only, an H^+ gradient across the membrane of about 3,000:1, or about 3.5 pH units, acid outside, is required. This is energetically equal to a $\Delta\varphi$ across the membrane of approximately 235mV, with the outside positive with respect to the inside (Mitchell, P., 1966). Mitchell suggested that the p.m.f. generated across the membrane of mitochondria may be a combination of a ΔpH of 1.0 and a $\Delta\varphi$ of about 150mV. Experimentation has shown that it is possible for electron transport to generate this membrane potential (Lehninger, A.L., 1975).

Jagendorf (Jagendorf, A.T., 1966) demonstrated that phosphorylation can be induced by an artificially generated ΔpH only. Also, Witt (Witt, H.T. *et al*, 1976) have proven that ATP synthesis can occur with an artificially generated $\Delta\varphi$ only. In their experiments isolated spinach chloroplasts were exposed to an external electric field strength (EEFS) of 1100 V/cm. To minimize deactivation of the enzyme, the applied voltage pulse was restricted to 30 ms and the system was cooled. Their results showed that the yield of ATP increases linearly with increasing number of pulses and they approximated that at least 6.5 ATP molecules were synthesized per ATPase by ten electrical pulses.

Similar experiments with rat liver mitochondria were attempted by Hamamoto (Hamamoto, T. *et al.*, 1982), however, the yield of ATP was too low to show a net turnover of the enzyme during a pulse. Their results did show that net ATP synthesis increased with increasing voltage, number of electrical pulses, and duration of electrical pulses.

Knox and Tsong (Knox, B.E. and Tsong, 1984) had greater success synthesizing ATP by electrically pulsing beef heart mitochondrial ATPase. They exposed cyanide-treated submitochondrial particles to higher voltages (EEFS=10-30 kV/cm) but shorter electrical pulses (1-100 μ s). Maximum yield was 10-12 mol ATP per mole ATPase per pulse for a 30 kV/cm-100 μ s pulse.

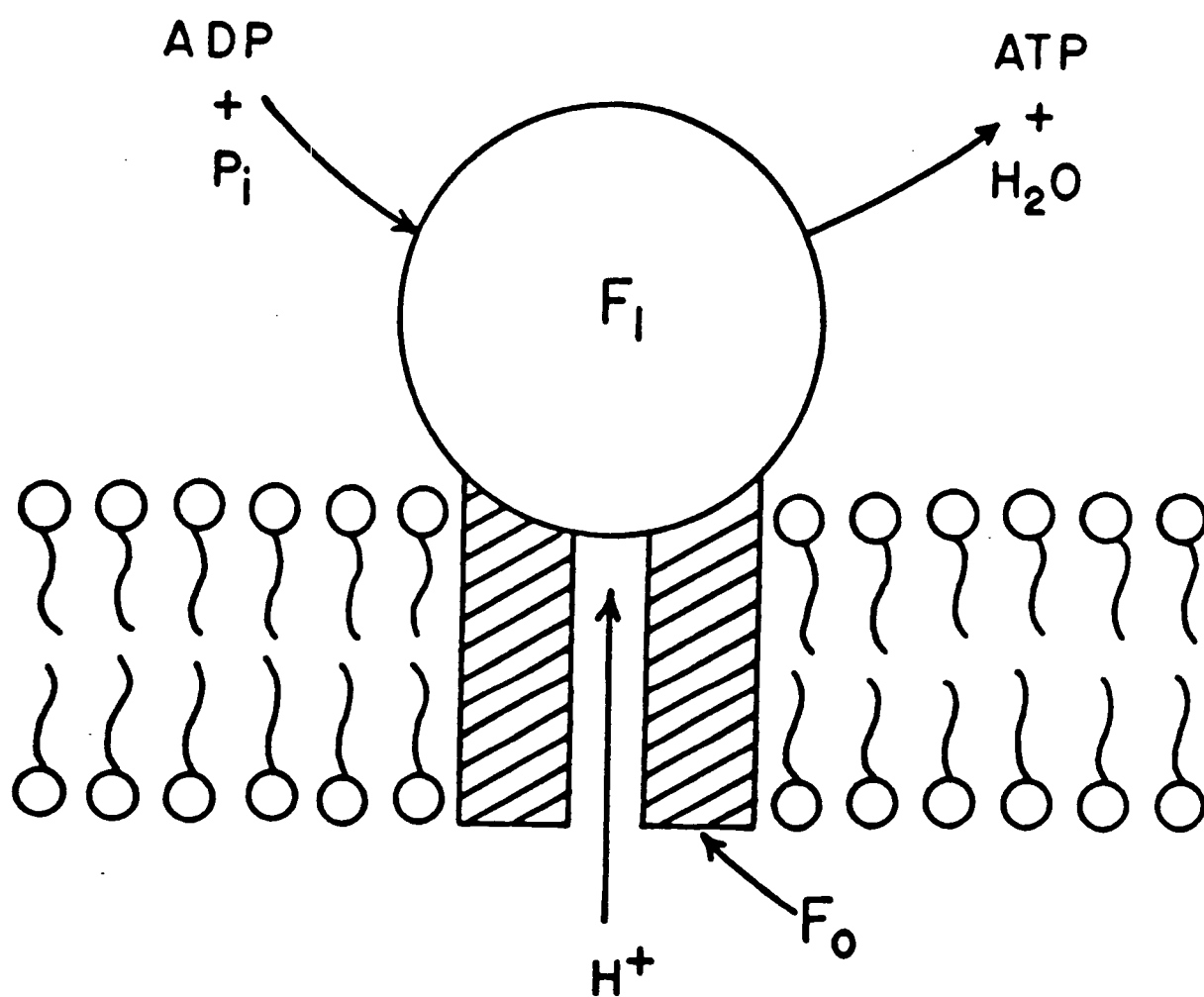


Figure 8.2. Schematic of ATPase.

The aims of the aforementioned studies have primarily been of a theoretical nature with no regard to scale-up potential. Since the vesicles are extremely small and are spherical or ellipsoidal, it is impossible to properly orient the ATPase with respect to a macroscopic p.m.f. to make use of all the ATPase. Therefore, for a workable artificial chloroplast, it would be more useful if the ATPase were immobilized in a macroscopic, planar membrane.

Proposed Methods

Recently, there has been an increasing interest in studying the interactions of proteins in biomembranes. Model membranes, either spherical liposomes or planar lipid membranes, may be used for resolution and reconstitution of specific proteins to investigate their functions. Problems arise with reconstituted model systems because they are not stable. To overcome this problem, Wagner (Wagner, N.K., *et. al.*, 1981) have incorporated the ATPase from *Rhodospirillum rubrum* into the synthetic lipid 2-[bis-(2-hexacosyl-10,12-diynoxyethyl)amino]ethanesulfonic acid. This sulfolipid contains a diacetylene group which allows it to polymerize upon UV irradiation (see Figure 8.3). These synthetic biomembranes seem to be completely stable. They cannot be destroyed by organic solvents (Hub, H.H., 1980). When bacteriorhodopsin was incorporated into this sulfolipid, its activity remained completely unchanged for more than three months (Pabst, R., 1983).

Planar bimolecular lipid membranes (BLM) are formed by one of two basic methods, the brush technique and the dipping technique. An overview of methods of experimental arrangements and procedures of producing ultrathin ($<100 \text{ \AA}$) BLM in aqueous solution is presented by Tien (Tien, H. Ti, 1974).

The formation of BLM in aqueous solution requires the creation of two coexisting solution/membrane interfaces. A thin piece of an inert material with a small hole is immersed in a dilute electrolyte. A small drop of a lipid is introduced to the hole where it will spontaneously thin by draining centrifugally to the lipid solution around the edge of the aperture, known as the Plateau-Gibbs border.

The brush technique was the original method of BLM formation. A small Teflon beaker with a small hole is set into a glass chamber and each is filled with a 0.1 M salt solution. The lipid is spread across the aperture with a fine sable hair brush.

The dipping technique may prove to be easier and to have fewer mechanical and technical problems. By the dipping technique, a metal, polyethylene, or hair loop of 1-

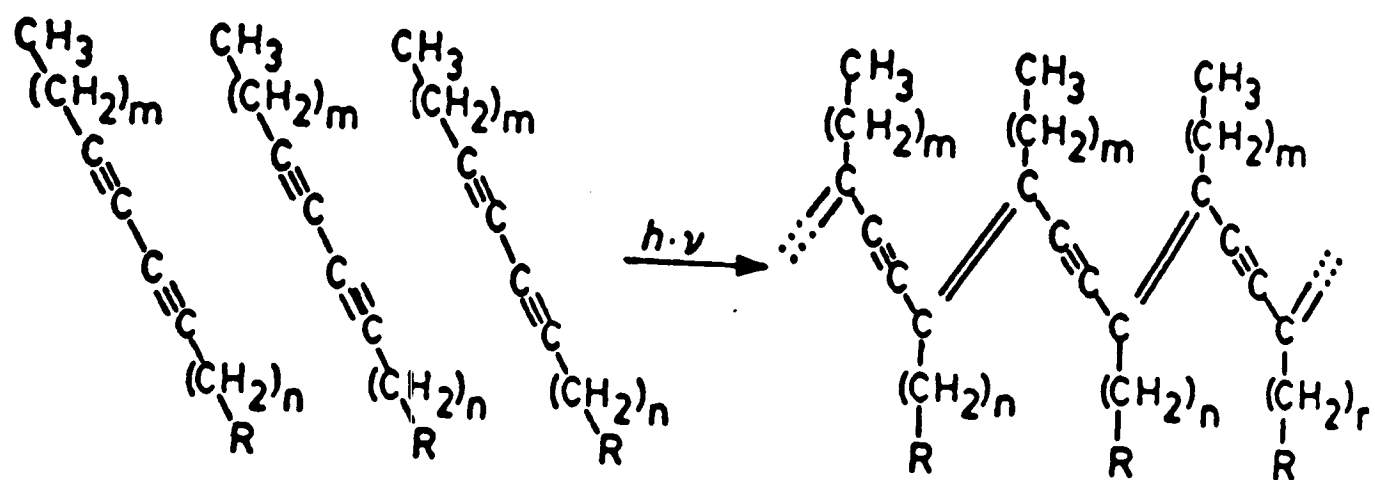


Figure 8.3. Cross-linking of diacetylene groups in the presence of ultraviolet light.

2 mm is dipped into a lipid solution and transferred through the air to a beaker filled with an aqueous solution. If a screen is used, this method may be preferable for producing large areas of membrane.

A method described by Takagi (Takagi, 1965) involves dipping a hydrophobic material through an air/water interface covered by a lipid monolayer. The tails of the lipids are pointed out of the water and therefore come together as the material is lowered. The surface pressure of the monolayer should be kept constant.

Similar to the above method (Montal, M., 1986), the hydrophobic material with the small aperture is above the air/water interface covered with a lipid monolayer. The liquid levels on each side of the pettion are successively raised and the two monolayers combine to form a lipid bilayer. The last two techniques described leave little or no solvent in the resulting BLM.

Figure 8.4 shows a schematic of the ATPase embedded in a BLM of the synthetic lipid. The BLM is formed with the synthetic lipid by one of the techniques described above on a screen mesh made of polypropylene or stainless steel. The ATPase is then added and it spontaneously orients itself in the membrane since the F_0 subunit is hydrophobic. The sulfolipid is irradiated with ultraviolet light to induce cross-linking. Although the cross-linking is not essential to the operation of the enzyme, it is desirable since it gives strength to the membrane.

Once the ATPase is immobilized in a macroscopic membrane, the enzyme may be powered by a pH or a voltage gradient. The simplest method to establish a proton gradient is to add a volatile acid to one side of the membrane as shown in Figure 8.5. Candidate volatile acids include hydrochloric acid, trifluoroacetic acid, and acetic acid. Alternatively, a volatile base, such as ammonia, could be added to the basic side of the membrane. The acid or base would be recovered by appropriate separation procedures such as vacuum distillation or adsorption.

Figure 8.6 shows a schematic of a more elegant method of creating a pH gradient electrochemically to power the enzyme. A minimum potential of 1.23V (the standard electrode potential (Castellan, G.W., 1971)) would be applied to the electrodes. In actuality, a higher voltage of about 2V would be needed to overcome losses in the system. At the anode, water is electrochemically split to form hydronium and oxygen. The oxygen will be added to the cabin for breathing. At the cathode, water will be split to form hydrogen and

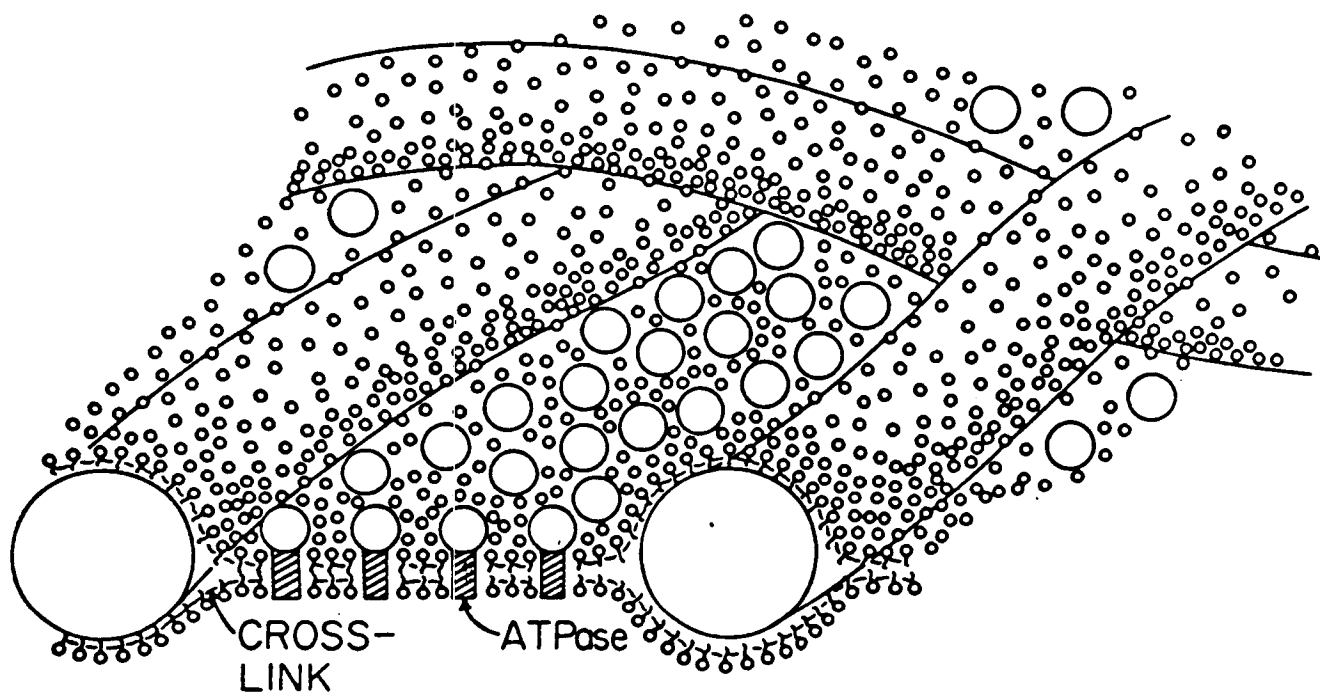


Figure 8.4. ATPase embedded in an artificial membrane.

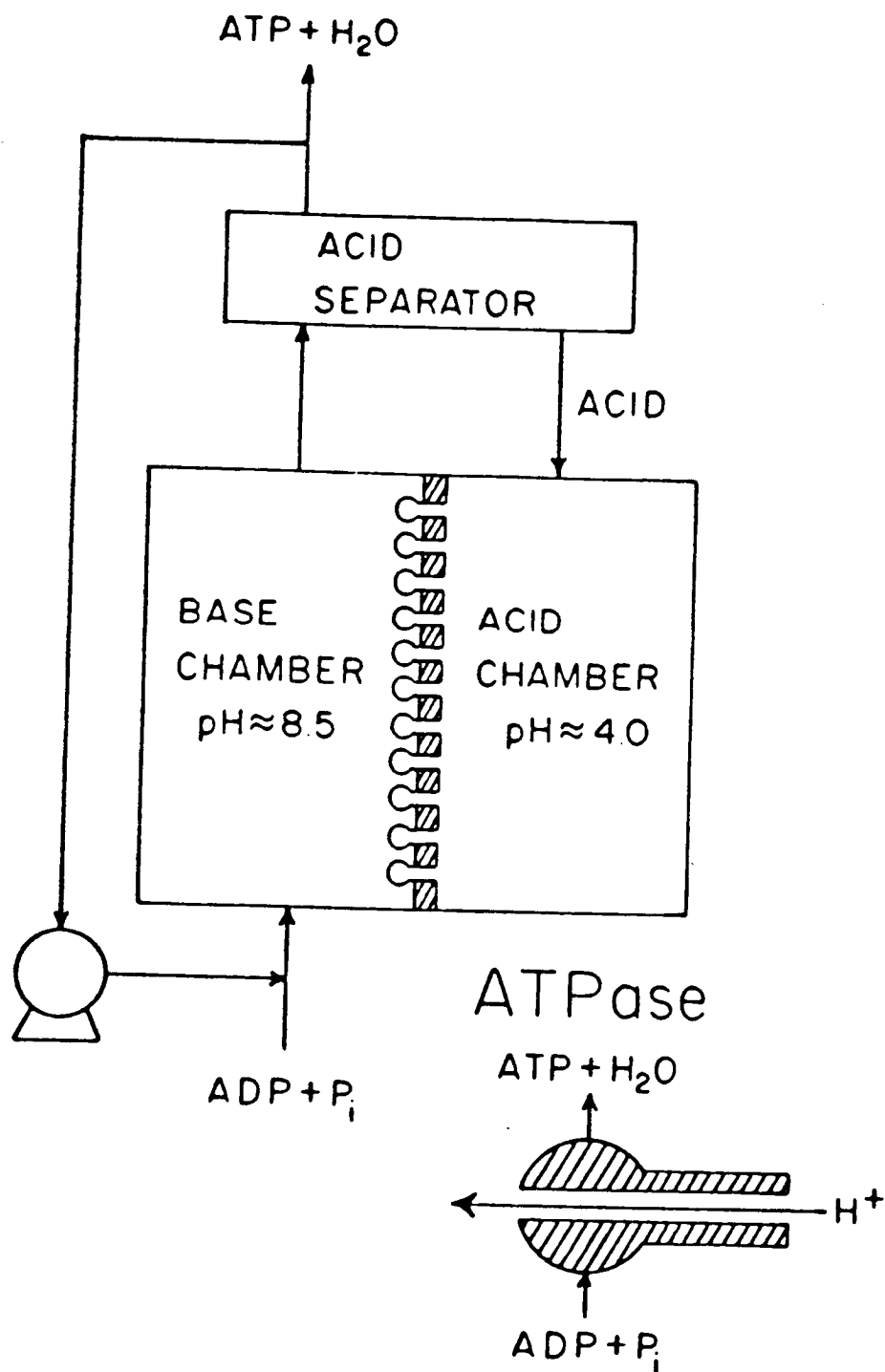


Figure 8.5. Regeneration of ATP using membrane-bound ATPase with a pH gradient created by addition of a volatile acid.

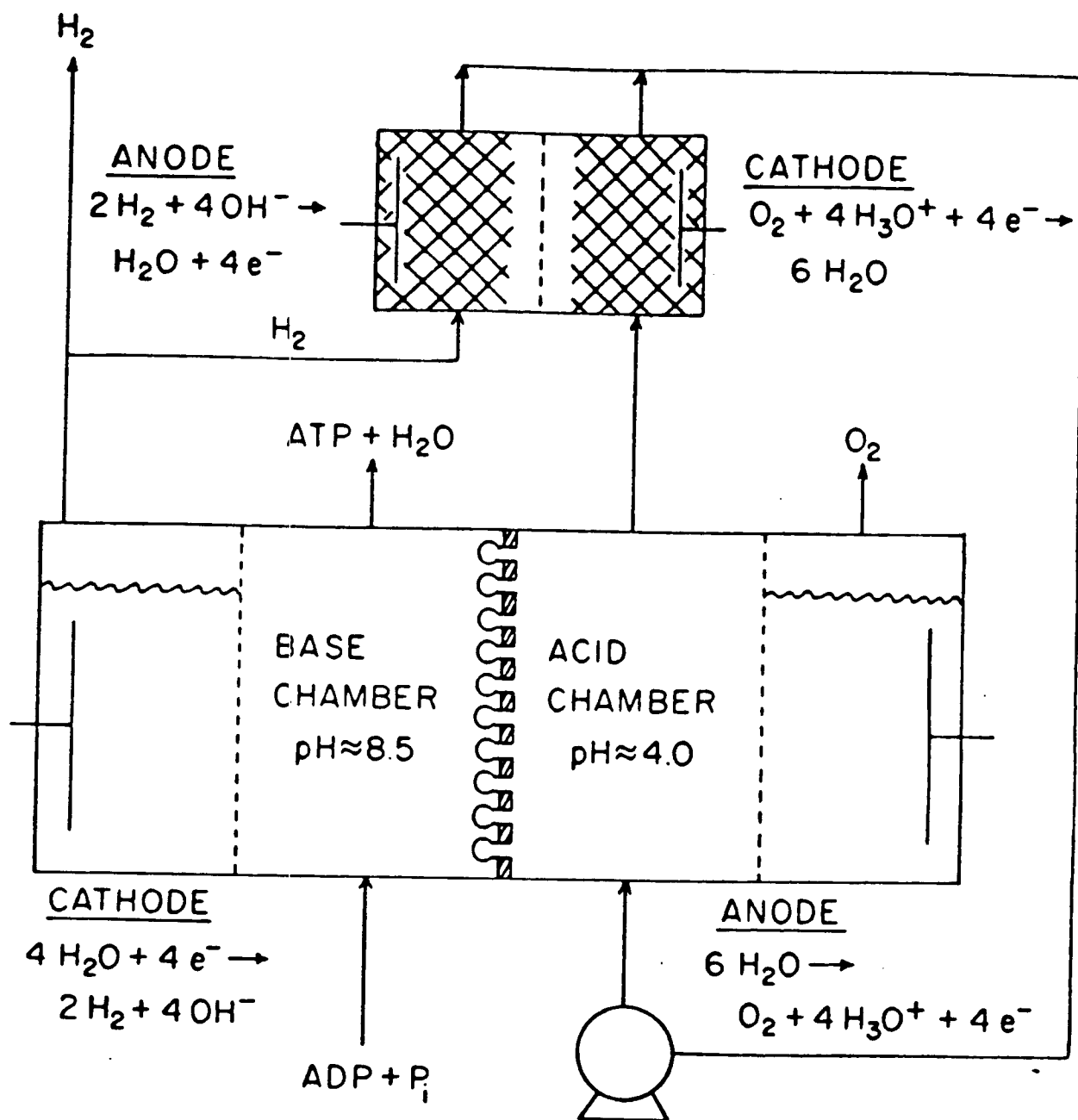


Figure 8.6. Regeneration of ATP using membrane-bound ATPase with an electrochemically produced pH gradient.

hydroxide ions. The hydrogen will be used to reduce NADP^+ . Thus, chamber 2 is more acidic than chamber 1. The protons (hydronium) will flow from the anode through the membrane-bound ATPase to the cathode to cause ATP to be regenerated from ADP. The electrodes are covered by proton-permeable membranes, such as Nafion (produced by Dow Chemical), to protect the enzymes and biochemicals. The hydrogen and oxygen products could be sold or fed to a fuel cell to help provide the electricity necessary to power the reactor.

As already mentioned, since some of the enzymes are susceptible to degradation by oxygen, the oxygen-laden liquid will be pumped through a porous catalyst which converts the oxygen and hydronium to water. Some hydrogen will have to be supplied to the anode to act as a sink for the electrons. This oxygen scavenging system will actually produce electricity since it is a fuel cell, however, it will have a relatively small power output since the oxygen is minimally soluble in water.

If a voltage gradient rather than a pH gradient is used to power the ATPase, the same apparatus shown in Figure 8.6 will be used, but rather than a small voltage of about 2V, about 1,000–20,000V will be used. This high voltage will be supplied in pulses using an electrical circuit similar to the one shown in Figure 8.7. The variable transformer will be set to a desired voltage and switch S_1 will be closed to charge the capacitor and then reopened. Switch S_2 will then be closed to discharge the capacitor through the cell and the resistors. The voltage drop across resistor R_2 is a small fraction of the total voltage drop so that a conventional voltmeter or oscilloscope may be used to measure the charge on the capacitor. Resistor R_3 is adjusted to control the time constant of the voltage discharge.

One of the major thrusts of the proposed research is to assess the relative merits of the two approaches to powering the ATPase. The pH gradient approach should be fairly "gentle" and easy to control compared to the use of a large voltage gradient. However, the voltage gradient approach should require the least amount of energy since a pure voltage with no current flow requires insignificant amounts of energy. In practice, however, it will not be possible to build up the voltage without some flow of current. The current flow can be minimized by reducing the ionic strength of the media and using an electrode material which has poor charge transfer properties. The studies which have been performed which apply a voltage gradient to ATPase have used platinum as the electrode material. Platinum has the best charge transfer properties of any known material (Bockris, J.O'M. and A.K.N.

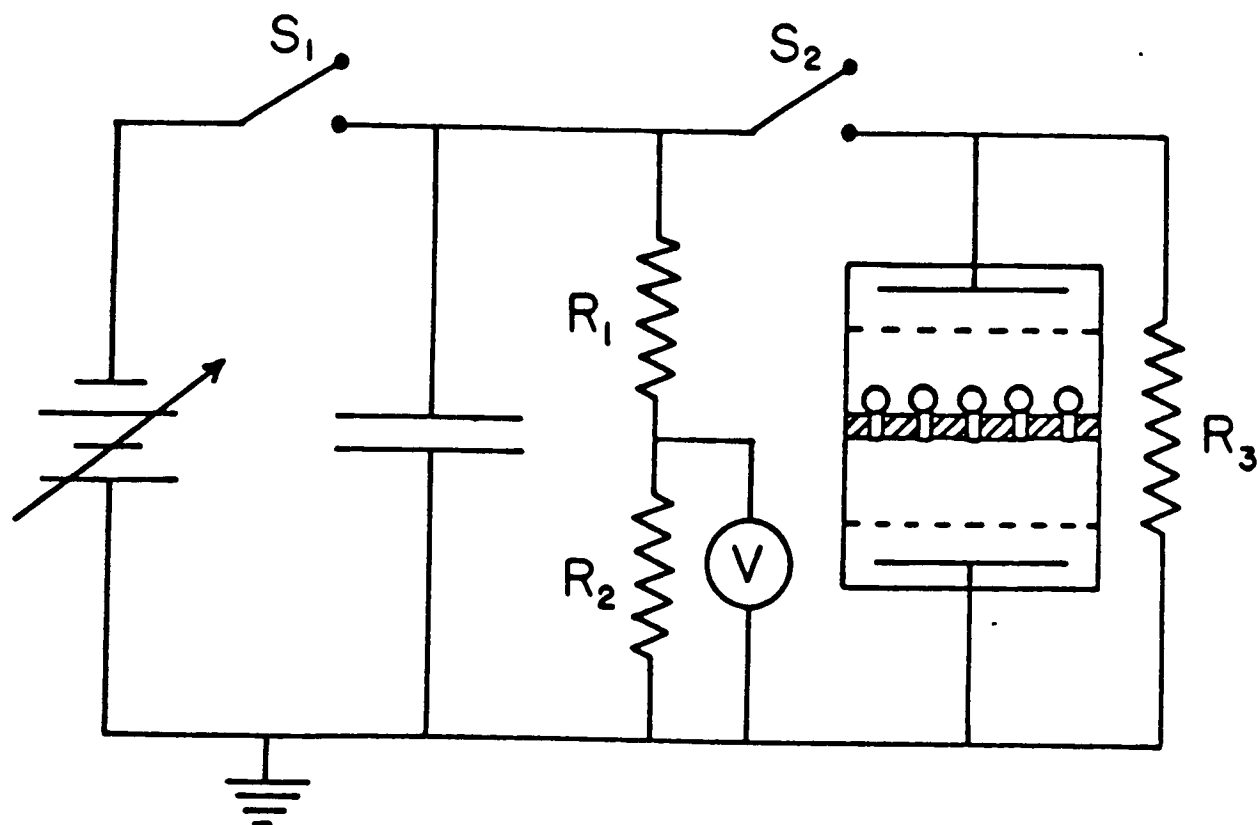


Figure 8.7. Schematic of the high voltage pulse generator.

Reddy, 1970), so it was the worst possible choice. It would be better to choose a material with poor charge transfer properties to reduce the current flow and hence reduce power loss and ohmic heating of the media. Graphite may be a good candidate material (Nguyen, T.).

Experimental Methods

Synthesis of the Polymerizable Synthetic Sulfolipid

The synthetic lipid 2-[bis-(2-hexacos-10,12-diynoxyethyl)amino]ethanesulfonic acid has been successfully synthesized in our laboratory by a method described previously by Hub (1980) as shown in Figure 8.8. All reactions are performed in an atmosphere of argon under a chemical hood. The first step is to synthesize the pentadecynyl iodide. 250 ml dried petroleum ether and 35 mmol of pentadecyne with stirring is placed in an ice bath. Add 22 ml *n*-butyllithium slowly, dropwise. A gel will form, so add petroleum ether if necessary. The mixture is now white and thick, so the precipitant may need to be broken up with a stirring bar. Let the mixture stir for 1 hour to assure complete deprotonation. The solution turns a light peach color. Add I_2 in 10% excess (9.8 g) as a solid. Allow 30–40 minutes of stirring to encourage a complete reaction. Transfer the mixture to an Erlenmeyer flask with 100 ml of H_2O and then into a separatory funnel. Remove the H_2O and wash consecutively with 50 ml of a concentrated solution of $NaHSO_3$ (twice), H_2O , and brine. Dry the solution with $NaSO_4$ to remove any remaining H_2O . The solution is a clear, yellow liquid. Evaporate the solvent off and the pentadecynyl iodide remains as an amber liquid. Place this product in a flask wrapped in aluminum foil and store in a freezer. Figure 8.9 and 8.10 shows the C_{13} and the H^+ NMR Spectra of the pentadecynyl iodide.

The second step of this synthesis is to make the carboxylate ion of undecynoic acid. Place 15 mmol undecynoic acid and 11.25 ml 10% KOH in a flask with stirring. Be sure the solution is basic ($pH \approx 10$). Add successively 75 mg hydroxylamine and a solution of 375 mg $CuCl$ and 3 g 70% aqueous ethylamine and allow to stir for 30 minutes. This solution contains the desired carboxylate ion.

Cool the solution containing the carboxylate ion in a water bath. Dissolve 15 mmol of the pentadecynyl iodide in 7.5 ml methanol. With vigorous stirring, add this solution to the solution containing the carboxylate ion very slowly dropwise (over a period of about 45 minutes). Allow this heterogeneous, dull yellow mixture to stir for 30 minutes. Remove the ice bath and allow the mixture to come to room temperature. Upon acidification with

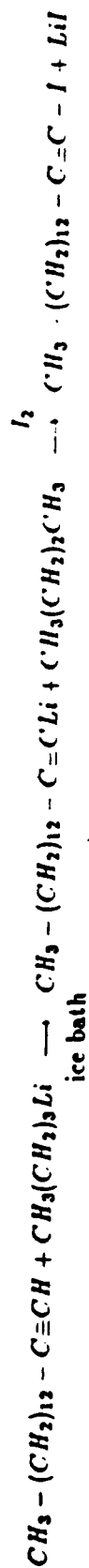
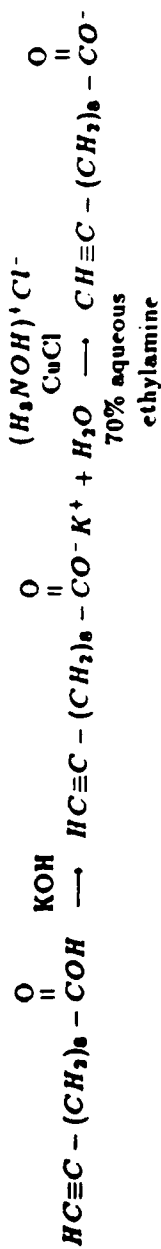
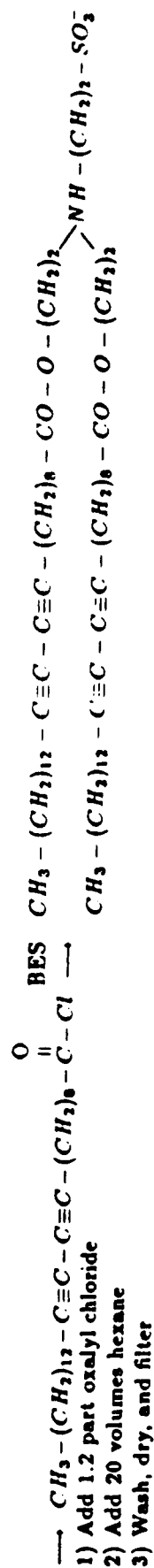
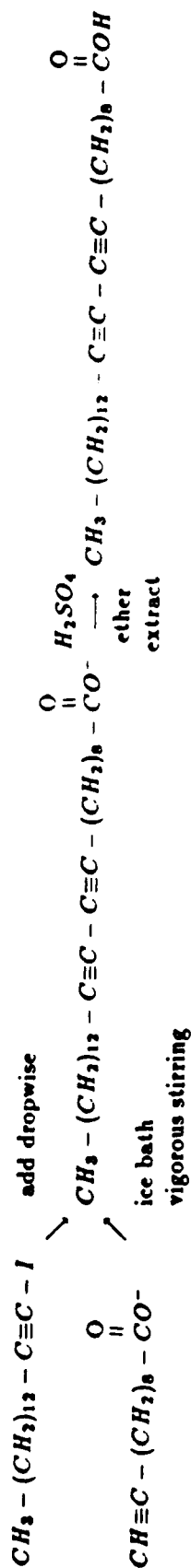
First StepSecond StepThird Step

Figure 8.8. Synthesis of the polymerizable synthetic lipid.

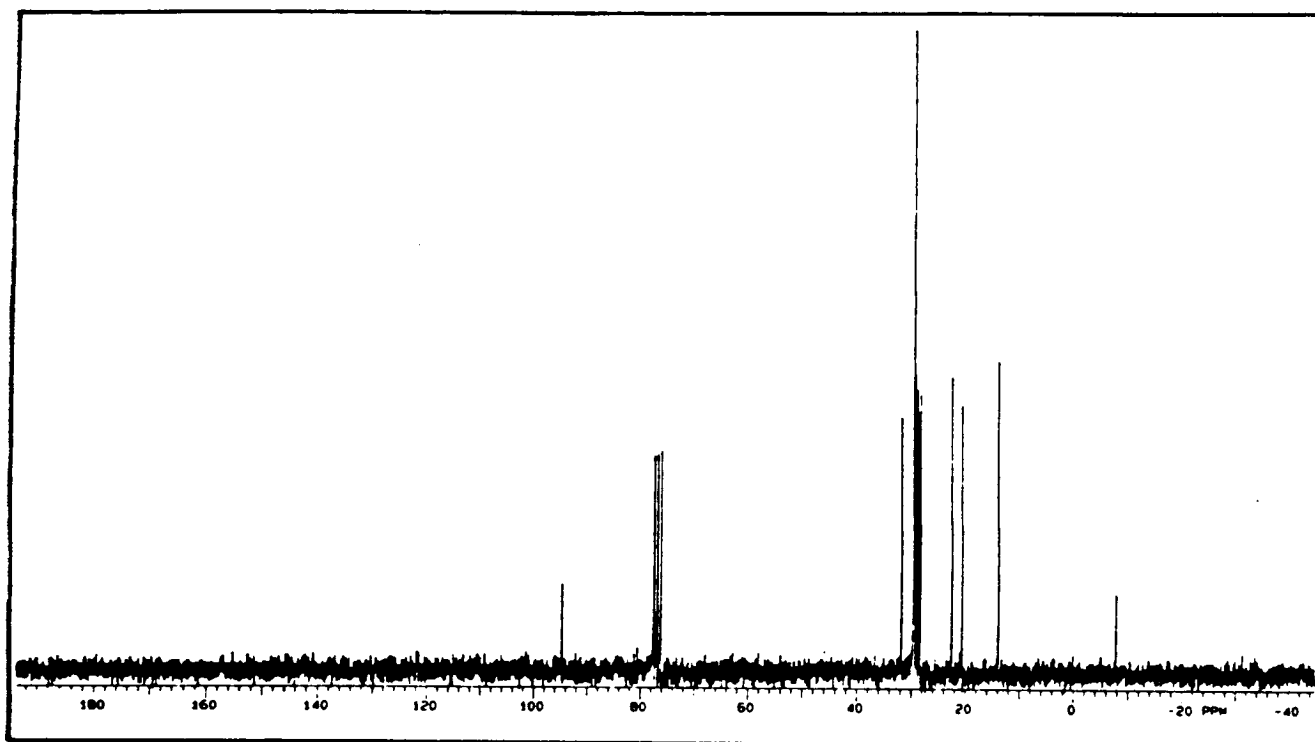


Figure 8.9. ^{13}C spectra of the pentadecynyl iodide.

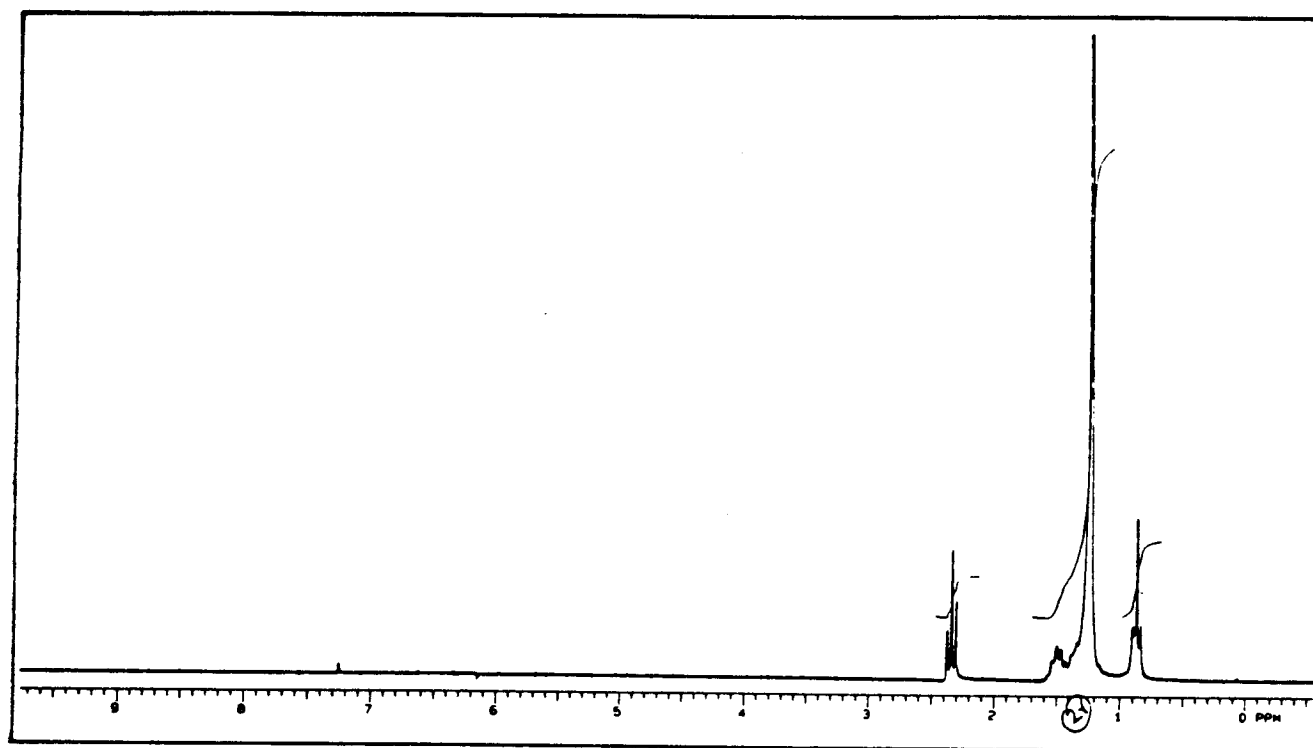


Figure 8.10. H^+ spectra of the pentadecynyl iodide.

2N H_2SO_4 (about 10–15 ml) the mixture turned brown and then pink. Extract with 30ml ether and wash the aqueous phase twice with 15–20 ml ether. Combine the organic layers and wash this solution with brine. Dry this clear yellow solution with NaSO_4 . Filter the solution and evaporate the solvent. Figure 8.11 and 8.12 shows the NMR of this acid. The melting point is 57–57.5 °C (56.5 °C was reported by Tieke (1976)).

Weigh the crystals (we had 1.98 g) and add about 2.38 g (1.2 times the weight of the crystals) oxalyl chloride. (Add enough oxalyl chloride to make a homogeneous mixture.) Upon addition of the oxalyl chloride HCl and CO are given off. Allow this solution to react in a flask covered with aluminum foil for 3 days with stirring. Place in an oil bath (70–80°C) and add a water aspirator for 30 minutes. Remove from oil bath and aspirator and allow the solution to reach room temperature. Add 20 volumes of hexane and transfer the solution to a separatory funnel. Wash three times with ice cold H_2O . Emulsions will form so encourage the separation with a glass rod. Wash with a small amount of brine. If solution is not clear, wash with brine again. Dry the solution with NaSO_4 . Allow this solution to stand for at least 15 minutes. The solution is a clear, yellow liquid. Evaporate the solvent. We have 4 mmoles of the acid chloride.

Mix the acid chloride with 0.426 g (N,N-bis[2-hydroxyethyl]-2-aminoethanesulfonic acid (BES) and add 7 ml chloroform. The BES does not quite dissolve. Add 0.485 ml pyridine and reflux overnight. We used an oil bath (about 60°C) and tap water for our cooling water.

Remove the oil bath and allow the solution to come to room temperature. Crystals may fall out. If crystals do not appear, evaporate part of the solvent off and place in a freezer. If crystals are reddish-brown rather than white, wash with methanol. Crystals are off white. Figure 8.13 and 8.14 shows the NMR spectra of the final product.

Membrane Formation and Immobilization of ATPase

The sulfolipid will be applied to a hydrophobic screen made of either stainless steel or polypropylene using the brush technique described above. The screen is immersed in an electrolyte solution of 0.1 M salt. A fine sable hair brush will be used to apply the synthetic lipid to the screen. Because the lipid is applied in a salt solution, it will properly orient itself since the charged sulfate heads will face the liquid side and the apolar tail will be located on the interior. Presently, we are learning how to make BLM's with lecithin as well as the sulfolipid.

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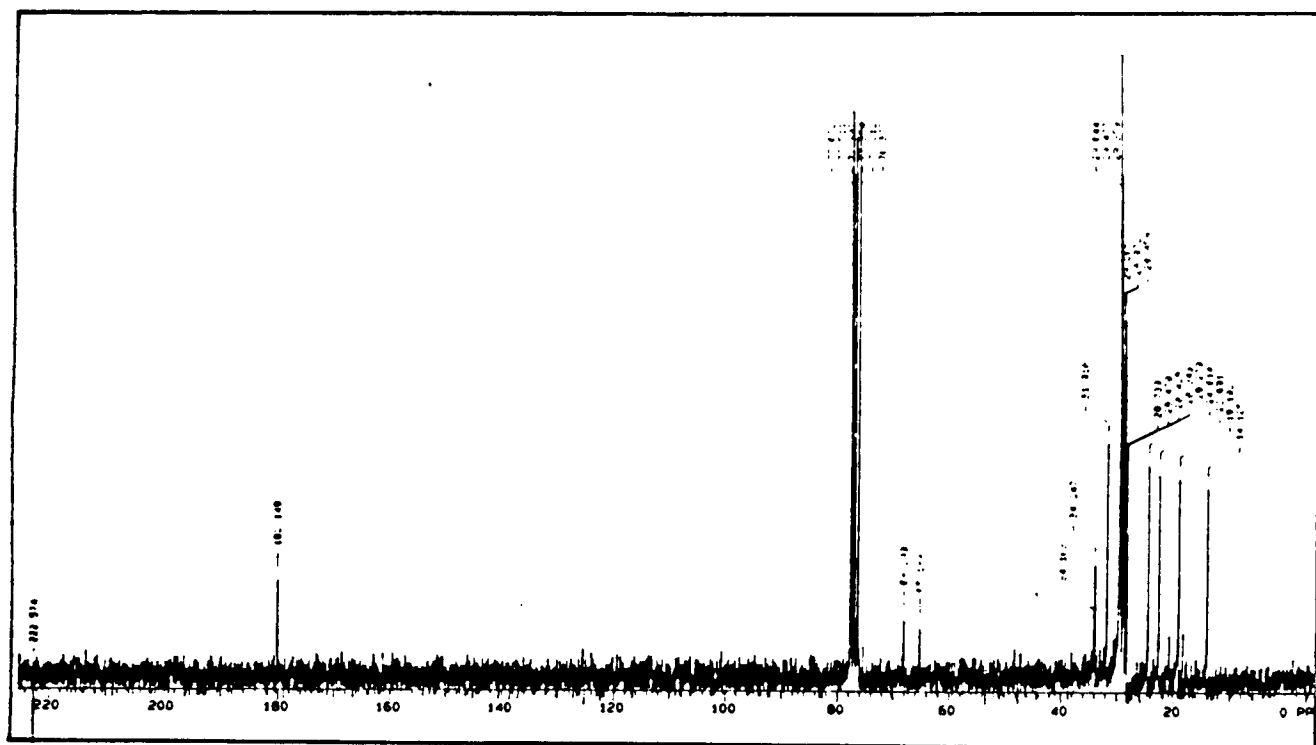


Figure 8.11. C_{13} spectra of the carboxylic acid intermediate.

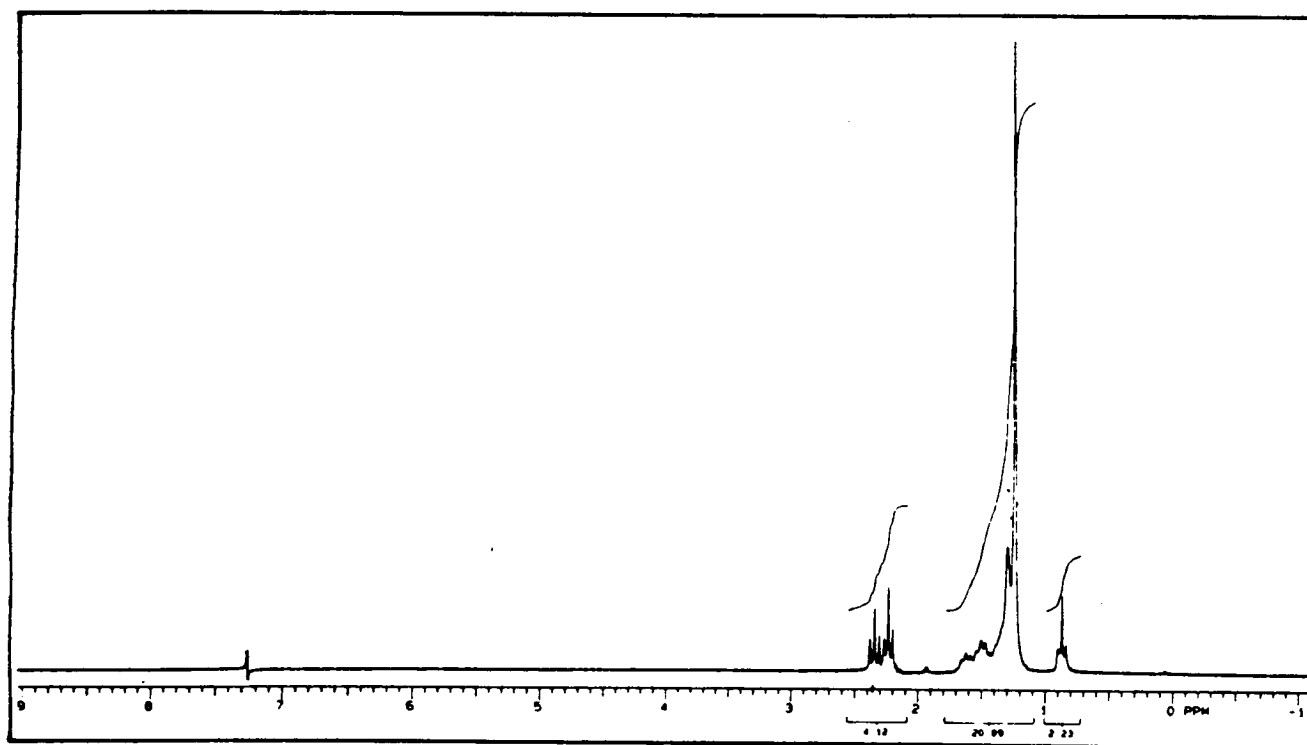


Figure 8.12. H^+ spectra of the carboxylic acid intermediate.

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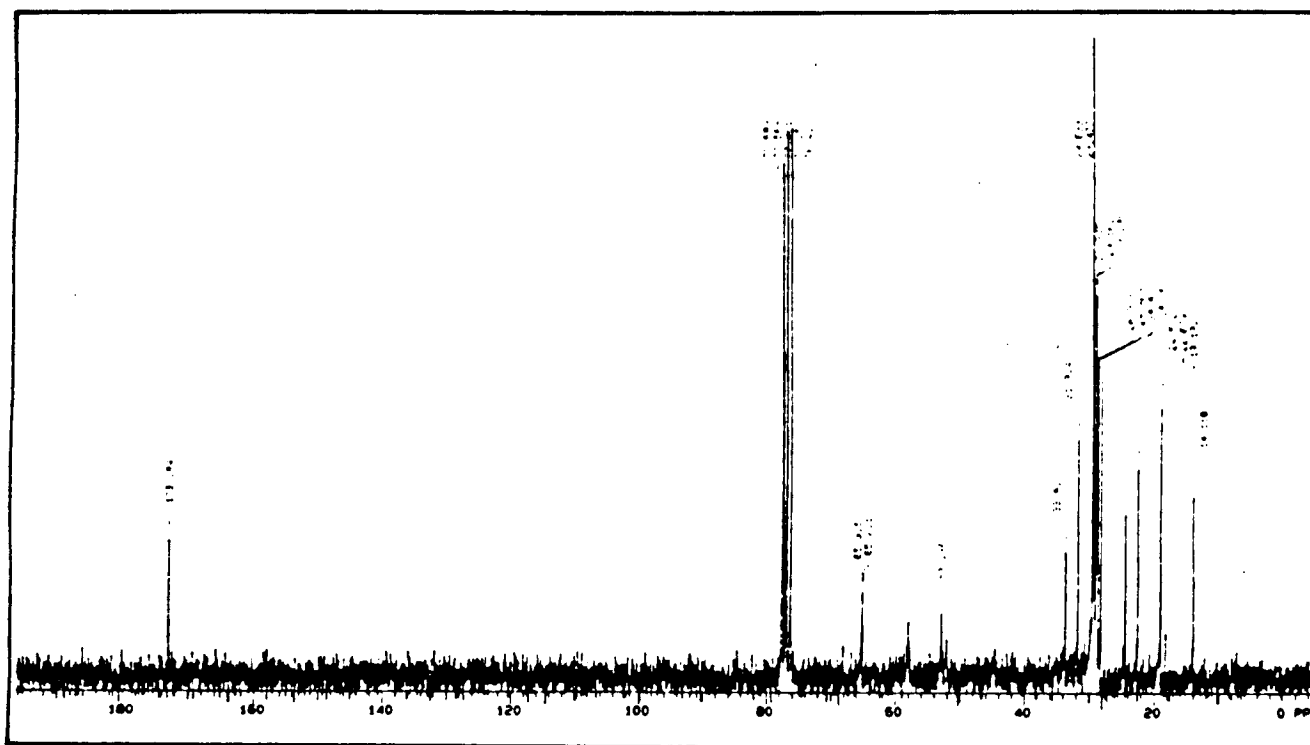


Figure 8.13. ^{13}C spectra of the synthetic lipid.

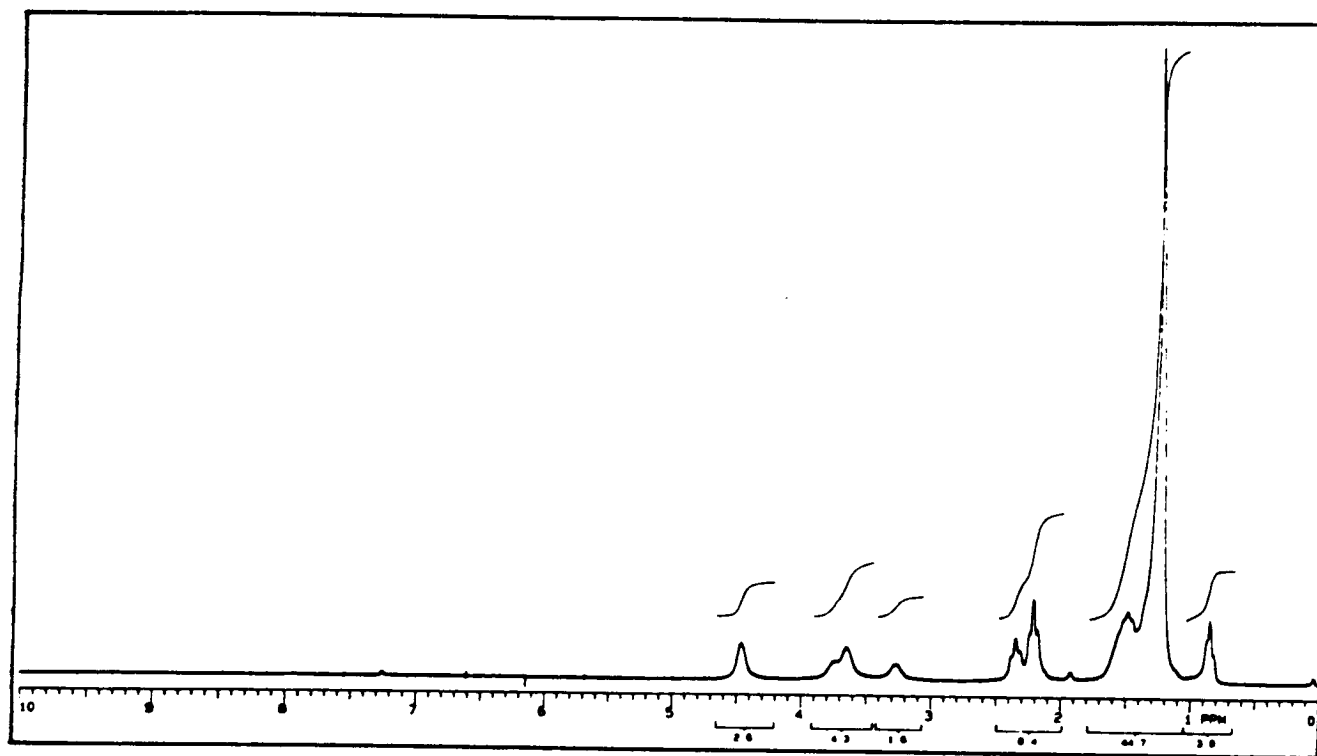


Figure 8.14. H^+ spectra of the synthetic lipid.

The ATPase, either purchased from Sigma or purified from *E. coli* (e.g. Fillingame, R.H., 1986; Friedl, P. and H.U. Schairer, 1986), will be added at ~50:1 lipid:protein (w/w) and incubated with the membrane for 10 min at 37°C (Wagner, N., *et al*, 1981). The ATPase should spontaneously orient itself into the membrane since the hydrophobic F_0 subunit will seek the apolar tails of the lipid. Once the ATPase is embedded in the membrane, the sulfolipid will be cross-linked to give the membrane structural strength. The diacetylene group of the synthetic lipid completely polymerizes in about 180 minutes at 254 nm with a light intensity of 0.09 J/m². An R-52G mineralight ultraviolet lamp from U.V.P., Inc. has been purchased for the polymerization.

Another, less elaborate method is to immobilize the ATPase in a polymer as shown in Figure 8.15. The ATPase can be placed in an aqueous layer with an immiscible organic solvent (e.g., toluene) on the surface. The ATPase should naturally orient itself at the interface, since the hydrophobic tail will attempt to go into the organic layer. A polymer (e.g., polystyrene) can be dissolved in the organic layer. The organic solvent will then be evaporated away, leaving the polymer as a membrane on the surface of the aqueous layer with the ATPase embedded in the proper orientation in the membrane.

The Reactor

Figure 8.16 shows the reactor assembly. The electrodes are placed in machined Plexiglas blocks. U-shaped Teflon spacers are inserted between the membrane and the Plexiglas. A rubber pad is placed behind the Plexiglas blocks to put some resilience in the stack. The resilience is necessary since Teflon cold-flows and will cause leaks. The entire assembly is held together by a vice to allow for easy assembly and disassembly.

pH Gradient Apparatus

The reactor shown in Figure 8.16 will have platinum electrodes. Current will be supplied by a commercial power supply which regulates the voltage to about 2 V.

Voltage Gradient Apparatus

The reactor shown in Figure 8.16 will have graphite electrodes. The voltage generator shown in Figure 8.17 has been custom made in the Texas A&M University Instrument Shop and is capable of supplying up to 20 kV pulses.

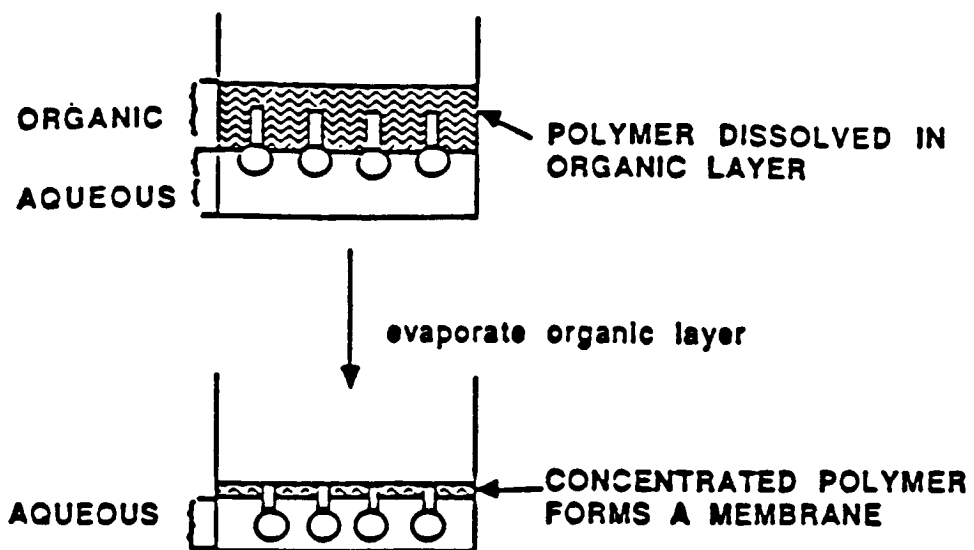


Figure 8.15. ATPase immobilized in a man-made membrane.

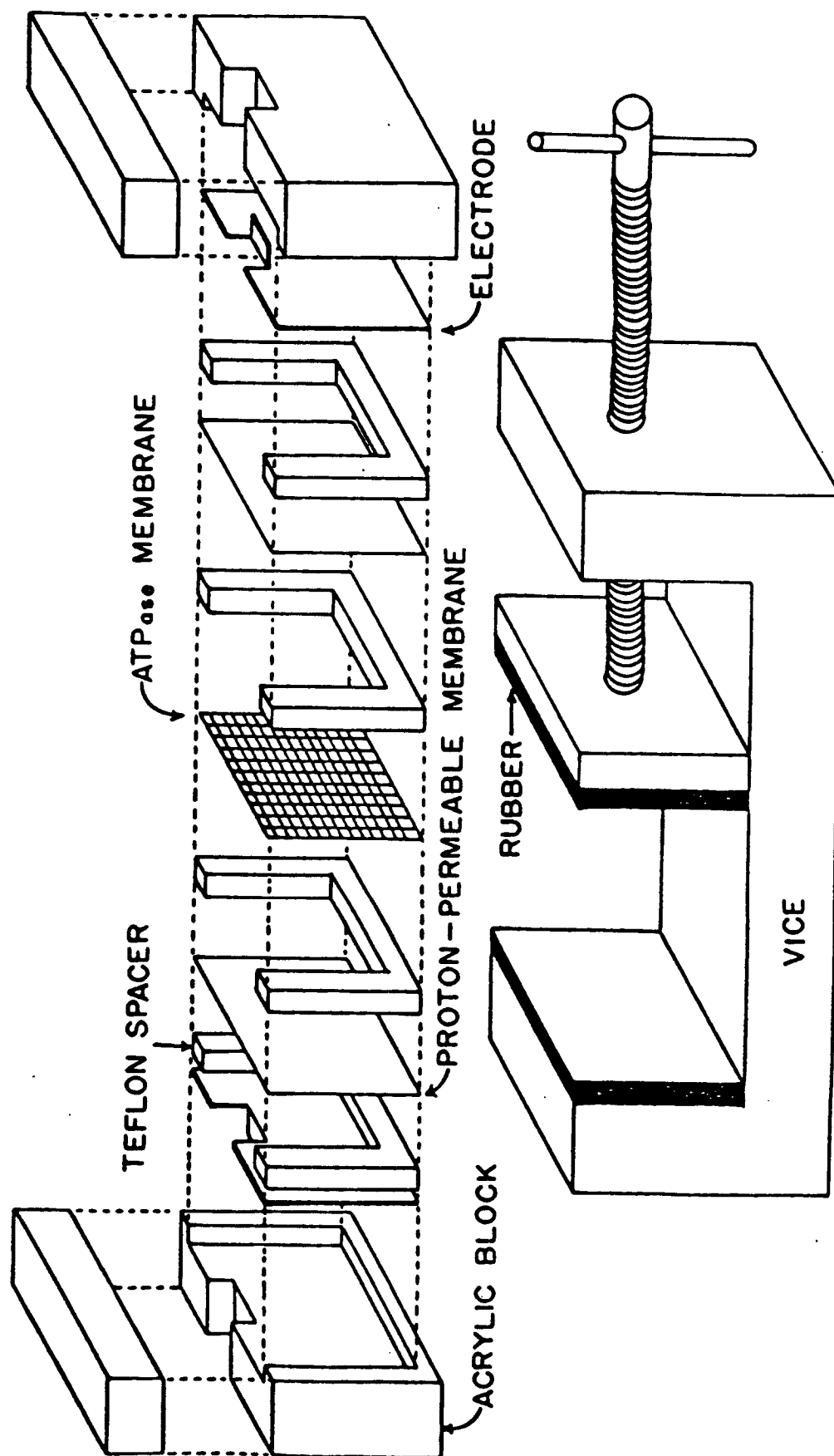


Figure 8.16. Reactor assembly.

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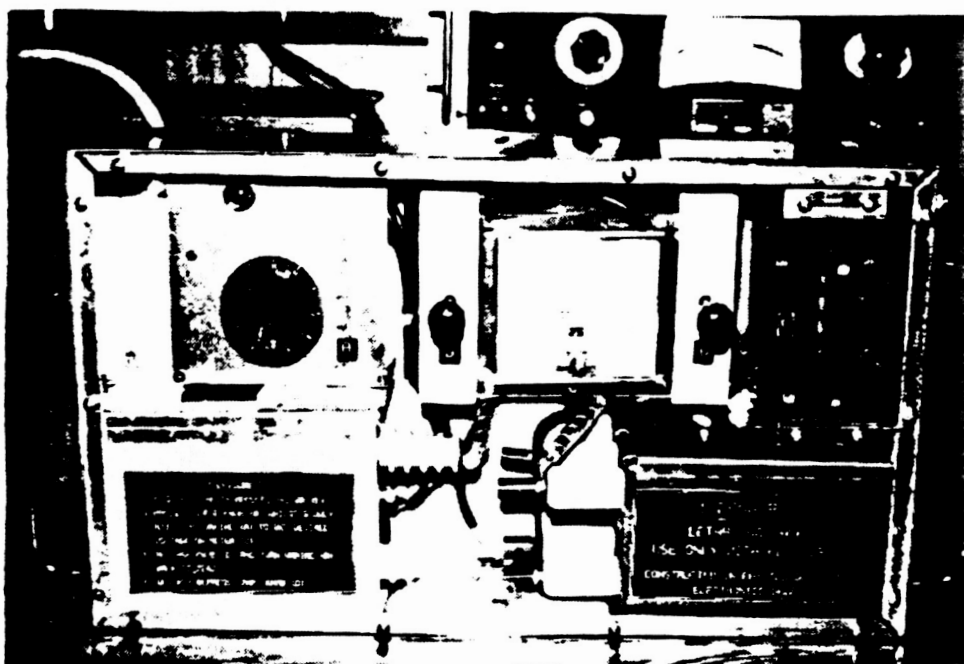


Figure 8.17. High voltage generator.

Operating Procedure

Buffered hexokinase, phosphate, and ADP will be placed in the reaction chambers formed by the U-shaped cups of the Teflon spacers.

In the case of powering the enzyme with a pH gradient, the current will be adjusted so that the pH of the enzyme solution stays within acceptable limits. The side where the acid is produced will have a dilute organic acid since the pH must be low to promote proton formation at the electrode surface. The types of studies which will be conducted are the stability of the ATPase, temperature studies, and the productivity as a function of input energy.

In the case of powering the enzyme with a voltage gradient, the voltage and pulse time will be adjusted to determine the optimum productivity of the ATPase.

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 9

INVESTIGATIONS OF LUNAR SOIL SIMULANTS

Prepared by

**R. Drees
L. Wilding
Soil & Crop Sciences**

Chapter 9

INVESTIGATIONS OF LUNAR SOIL SIMULANTS

Research emphasis has focused on the development of lunar simulants. Due to the lack of lunar materials for examination and evaluation, the initial phase of the project involved the collection and evaluation of terrestrial deposits that have similarities to lunar materials. This will form the basis of the initial study. Appropriate lunar simulants are significant in evaluating short-term and long-term weathering reactions, secondary weathering products and mineral equilibria.

In support of this research, several studies have been initiated to identify the specimen(s) which are most similar to lunar materials:

- 1) During the summer of 1987, rock samples were collected by Dr. L.P. Wilding from ten potential locations in various portions of Iceland. These samples represent a variety of basalts, lavas, mafic-rich obsidians and plagonites of varying texture, mineralogy and composition. Several site locations have been documented in the literature (Jakobsson, 1972, 1980; Oskarsson, et al., 1982). and appear to have chemical and mineralogical composition similarities to lunar materials, but full characterization will be required to match silicate compositions with lunar samples. After this is completed, a determination will be made on additional samples that will need to be collected in Iceland in 1988. A brief description of the samples collected and approximate location is given on the accompanying table and figure.
- 2) Rock thin-sections have been prepared for each site location to document the spatial *in situ* distribution of minerals within the sample. This phase of the study can be correlated with petrographic analysis of lunar material.
- 3) X-ray diffraction analysis of the total sample to evaluate mineralogical composition of Icelandic samples is underway. Preliminary analysis indicate that the samples are composed primarily of plagioclase feldspars and olivine, which are among the more common minerals on the lunar surface. Quartz is a minor or trace component which is also similar to lunar materials. This preliminary analysis is in agreement with available geological data.
- 4) Total elemental assay by x-ray microprobe analysis will be conducted in conjunction with Dr. Doug Ming at NASA, Johnson Space Center. This phase of the research has just been initiated, and no results are available at this time. Results from these analyses will be compared to comparable microprobe analyses performed by JSC on lunar samples.

Table 1. Description of Samples collected for Lunar Simulants (see the following map for approximate site location).

<u>Sample #</u>	<u>Description</u>
R-1	Basalt-rich glacial till from C2 Horizon (35-60 cm). The fines were from basaltic material, little oxidized since deposition. Particle size distribution appears to approximate lunar materials.
R-2	Basalt rocks collected from C2 horizon (35-60 cm) at same site as R-1. Geological date from this area indicates basalts that are in the tholeiitic series: a relatively high content of Fe and Ti, and a low content of Al and Ca. This composition approximates lunar materials.
R-3	Mafic-rich lava with Ca-rich plagioclase phenocrysts. Site is about 10 km east of Reykjahlid. Lava field is about 3000-5000 years old. Same geologic area as R-1 and R-2.
R-4	Glacial gravel below Hoffellsjokull glacier. Samples are black, dense mafic-rich basalts with small feldspathic phenocrysts.
R-5	Base-rich and dense palagonite from landslip about 10-15 km NE of Kirkjubaejarklaustur. The area from which samples R-5 through R-9 were collected is represented by transitional alkali basalts. These rocks are characterized by a high content of Fe and Ti, and low Al. Many of the lava flows are olivine-rich tholeiites.
R-6	Less base-rich bedded rhyolite rock which has been cemented and fused into palagonite. Collected at same site as R-5.
R-7	Sample collected from an 1873 lava plain-moss covered landscape about 8 Km W of Skafta bridge. Sample highly variable in composition, sharp and vesicular.
R-8	Very vesicular sample collected from 1000 year old lava field near Eldgia. Sample collected about 5 cm below zone of moss and lichen weathering.
R-9	Obsidian-like sample from columnar stack near hot geothermal spring at Landmannalaugr. Area has abundant rhyolite and other geothermally altered green rocks.

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 10

**FOOD PROCESSING FOR LIFE SUPPORT
SYSTEMS**

Prepared by

J. Wagner
Food Protein Research Center

Chapter 10

FOOD PROCESSING FOR LIFE SUPPORT SYSTEMS

Introduction

The permanent presence of humans in space requires efficient life support systems that satisfy basic human dietary needs for food. NASA has identified eight plants including wheat, rice, white or Irish potato, sweet potato, soybean, peanut, lettuce, sugar beets for intensive study on growth, harvesting and processing in a space environment. A key component of this system is a procedure by which these crops can be processed easily into edible, nutritious foods without requiring excessive lift-off weight, energy and time.

The primary emphasis of our study is placed on plants or cultivars that pose the most processing difficulties - wheat, rice and soybean. That is, we propose conventional microwave heating for white and sweet potatoes and sugar beets, dry roasting for peanuts and no processing whatsoever for lettuce. Wheat, rice and soybean contain outer protective shells or hulls that protect the inner nutritive portions from the environment. An oil bearing seed such as soybean would typically require cleaning, thermal preconditioning, cracking, hull separation and thermal conditioning prior to conventional extraction methods to obtain edible oil. Conventional cleaning, cracking and hull separation procedures require a gravitational field and thus would not be applicable in space. Rice and soybean contain antinutritional factors that can be deactivated by cooking or by other thermal methods.

Research at the Food Protein R&D Center at Texas A&M has shown that extrusion of soybean and rice bran can be used to inactivate the enzymes associated with these plantings. Additional studies have also shown that edible products can be made from combinations of whole soybean, whole white corn, ground degermed white corn and ground wheat flour by heating in a single step in a short residence time extruder. A breakthrough by a Canadian researcher uses enzymes to liberate oil by destruction of oil pocket membranes present in soybean, rice bran and peanuts. This technique affords the potential to minimize or eliminate complex, high-cost mechanical and/or thermal pretreatment operations for soybean and possibly for wheat and rice.

A major component of food production research for life support will be to integrate knowledge related to food processing technology with other aspects of growing foods in a permanently manned space environment. These considerations include (1) specifications for plant growth conditions and facilities, including biomass of food output, nutritional quality, energy requirements, thermal control and plant

growth regimes; (2) gravitational considerations; (3) available manpower and man-hours (i.e., how much of an astronaut's time is to be devoted to food growth and processing); (4) transport between Earth and space or lunar bases. Many of these criteria are still in the investigative stage. The adaptation of food processing technology to space environments (orbiting space station, Lunar base, Mars missions) therefore becomes a critical component to the successful conquest of space.

Overall Objectives of the Research

Proposed study will concentrate on developing new processing equipment designs and procedures aimed at minimizing or eliminating water and simplifying complex processing flowcharts (e.g., as for wheat, rice and soybeans). The long-term objectives of this proposed project are:

1. to develop novel methods and procedures for separating proteins, single and complex carbohydrates, fats or triglycerides, fiber and gums from the selected plants;
2. to reconstitute the constituents in an optimum manner from nutritional, taste, flavor, and texture viewpoints; and
3. to institute a sensor development and evaluation program required for continuous monitoring of changing food properties during processing.

The primary emphasis of this proposed study will be on the three selected plants that pose the most processing difficulties, wheat, rice and soybean. We propose conventional microwave heating for white and sweet potatoes and sugar beets, dry roasting for peanuts and no processing at all for lettuce.

Methodology

To achieve these objectives, research and engineering studies will be carried out to (1) critically review processing equipment with emphasis on miniaturization and single-step equipment integration; (2) evaluate and/or develop enzymes for hull degradation that can be deactivated by thermal means when warranted; (3) analyze the kinetics of enzyme degradation of hulls and oil product membranes in soybeans, peanut and rice bran (cellulase, pectinase, hemicellulase, glucanase and amyloglucosidase will be evaluated for oil pocket membrane degradation); (4) develop extrusion methodology for combinations of the seven NASA plants (excluding lettuce) identified for intensive study, and (5) evaluate state-of-the art advanced sensing techniques based on fiber optic UV-VIS-NIR analysis, NIR reflectance, NMR, in-line process refractometry, RF dielectric constant and microwave analysis.

Resources Available and Needed

The Food Protein R&D Center at Texas A&M operates the most modern and comprehensive oilseeds research facilities of any university in the United States. Both laboratory and pilot scale food extrusion and processing facilities are available for preparing formed protein, cereals, mass feeding foods and other types of experimental products. A protein isolate pilot plant contains protein extraction tanks,

ultrafiltration and reverse osmosis equipment, continuous centrifuges and decanters, spray dryers, drum dryer and a small can closing and retorting facility. In addition, laboratories for separations and ingredients sciences research, bioengineering, biochemistry, physical chemistry, industrial microbiology, process engineering and product applications research are also available. The Center's Research Oil Mill at the Texas A&M Research Extension Center contains five pilot plants for seed processing, solvent extraction, industrial crops processing, hydrogenation, and oils and fats refining.

In addition to the above facilities already available at the Food Protein Center, sophisticated instrumentation will be needed for continuous monitoring of changing food properties during processing and storage. Various state-of-the-art sensors and instrumentation require evaluation for ease of operation and whether they can function in an on-line, in-line or only in a clean laboratory environment. Equipment which must be obtained and tested include:

Item	Function
1. UV-VIS-NIR analyzer	Advanced spectrophotometrics between 200-2,200 nm will permit general chemical analysis of compounds in real time, on-line or in-line with a fiber optic probe up to 200 meters away from the sensing electronic hardware.
2. NIR reflectance analyzer	A proven method for reliably determining protein, moisture, sugars and oil content in a lab environment.
3. In-line process refractometer	Rapid analysis of sugars in water, starch concentration, and acids or bases in water.
4. NMR analyzer	On-line analysis of various chemicals and oil content in seeds containing the hulls without sample preparation.
5. IR moisture analyzer	On-line analysis of moisture in foods and oilseeds.
6. RF dielectric constant analyzer	On or in-line analysis of moisture in bulk samples.
7. Microwave moisture analyzer	Lab instrument for bulk or surface moisture analysis.

The Biosystems Research group have available a laboratory equipped with plant growth chambers and associated equipment. The modeling portion of the project will draw upon resources available through the RECON group for hardware and experts.

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SECTION III

INTERDISCIPLINARY RESEARCH

Chapter 11

**PRELIMINARY STUDIES FOR AN ENCLOSED
CROP GROWTH CHAMBER ON THE MOON**

Prepared by

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Chapter 11

PRELIMINARY STUDIES FOR AN ENCLOSED CROP GROWTH CHAMBER ON THE MOON

This report provides an overview of specifications for an enclosed, self-contained crop growth chamber capable of providing caloric requirements for a permanently manned lunar base. Included in the discussion are lunar environmental conditions, chamber construction specifications, lighting and power requirements, thermal control, water and nutrient cycling, and growth conditions for each of several crop plants.

THE LUNAR ENVIRONMENT

Temperatures at the lunar surface vary widely over the course of a lunar day (14 Earth days in the light, 14 in the dark), with measurements ranging from a low of 102K (-171 °C) to a high of 384°K (111 °C). Temperature variations are damped out rapidly with soil depth, so that at 30 cm temperature remains a fairly constant 250°K (-23°C) (Keihm and Langseth, 1973).

The moon is not very active geologically. The relatively few moonquakes that have been recorded by Apollo seismographs have been weak compared to earthquakes. The lunar soil, or "regolith," is a global veneer of debris and dust, of comparatively low density ($1.9/\text{cm}^3$) and high porosity, overspreading the comparatively stable lunar "bedrock." The regolith averages 5 to 10 meters in depth, although occasionally it reaches a depth of 30 meters. The thermal conductivity of the regolith is extremely low, from 0.9 to $1.3 \times 10^{-10} \text{ w cm}^{-1} \text{ K}^{-1}$ at depths greater than 30 cm, and its thermal diffusivity is 0.7 to $1.0 \times 10^{-4} \text{ cm}^2 \text{ sec}^{-1}$ at comparable depths (Langseth et al. 1976). The lunar soils thus provided a stable platform and acts as an excellent insulator (Taylor, 1986).

The effective absence of an atmosphere means that little protection is provided against various energy sources from space and from the micrometeorite flux. Incoming electromagnetic radiation runs the spectrum from high-energy radiation types (ultraviolet, X-rays, and gamma rays) provide cause to worry. Also of note is the solar wind, the more or less continuous emission of charged particles from the sun. During periods of solar flareups the solar wind reaches intensities so that about two meters of regolith are required for protection (Taylor, 1975). The micrometeorite flux is considerably higher on the Moon than on the Earth, and even the smallest meteoroids impact upon the lunar surface with full deep-space velocity ($>10 \text{ km/sec}$). The potential threat to humans or equipment on the Moon is obvious.

SPECIFICATIONS FOR PLANT GROWTH CHAMBER

Specifications for the enclosed crop growth chambers are based on a series of design studies of various controlled ecological life support systems and scaled here to support the caloric needs of four men. There are four basic requirements for human support in such a system: food, oxygen, drinking water and sanitary water. In one year a typical 70kg male requires three times his body mass in food, four times his mass in oxygen, eight in drinking water, and twelve in sanitary water (Murray and DeJonge, 1986).

The intensive "farming" necessary on a lunar growth chamber will allow a significant reduction in plant growth area as compared to Earth. Estimates of the precise area required on a space-based station vary slightly from 20 m² per person (Olson et al., 1987) to 25 m² per person (Henninger et al., 1986; Wheeler and Tibbitts, 1987). A plant growth surface of 100 m² was adopted here as sufficient for four people. Furthermore an atmosphere reservoir of 100 m³ for the agricultural area (exclusive of the 200 m³ for the crew area) is estimated (Henninger et al., 1986). The precise architectural "blueprint" of this chamber must be deferred until further requirements, including those beyond the scope of this report, are considered. The prototype Controlled Ecological Life Support System (CELSS) however, will probably be derived from a series of standard space station modules (SSM) as the basic housing, work and plant growth unit, with interface modules interconnecting these, and all buried 2 m beneath the regolith surface as protection from solar wind flares and the meteorite flux (Figure 1) (Roberts, 1986). This report describes specifications for a plant growth chamber (PGC) using the SSM as the basic construction unit.

LIGHTING AND POWER REQUIREMENTS

Studies on wheat growth in controlled space-related environments indicate that 750 mE m⁻² s⁻¹ was a beneficial illumination level (Bugbee and Salisbury, 1985). Some plants show more shade intolerance than others, however, and to provide adequate illumination for any of the potential crop plants on the Moon an illumination of 1,000 mE m⁻² s⁻¹ is adopted here.

Three plant illumination systems could meet the requirements of the lunar plant growth chamber: (1) A direct solar collection system using fiber optics. (2) Exclusive artificial illumination. (3) Solar illumination with supplementary artificial light. Each has advantages and disadvantages.

Solar Light Full Intensity Illumination

A fiber optic solar collection system collects sunlight, which is conducted through fiber optic cables to emitters over the plant types. Lenses may permit selective light frequency collection and transmission to filter out UV and IR. Reflectors over each emitter and silvered surfaces inside the plant growth units serve to reflect light onto the plants. Based on a solar-illuminated fiber optic system designed by Oleson et al. (1987), a solar collector of 210 m² area is sufficient to provide 1,000 mE m⁻² s⁻¹ over 100 m² of plant growth area, assuming 100% transmission efficiency of light from collector to emitter (an optimistic assumption, see below).

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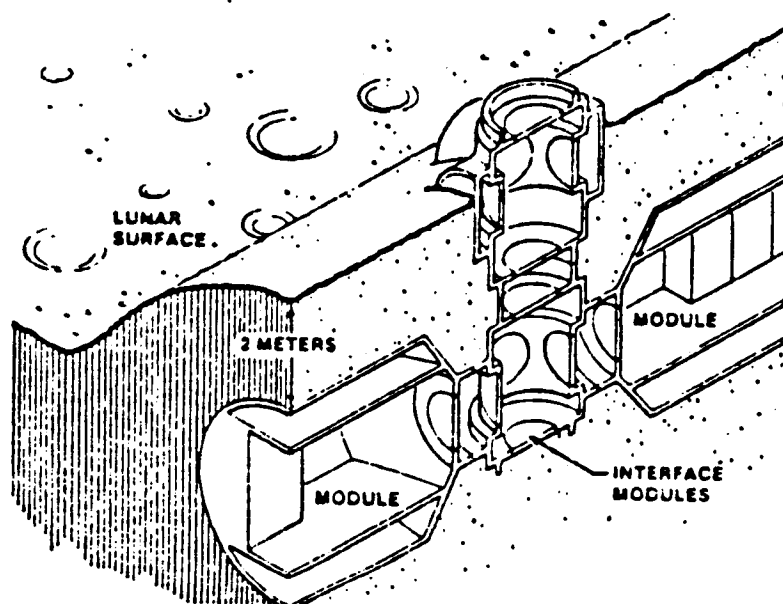


Figure 1. The first lunar base habitats and laboratories could be Space Station modules, buried in the lunar regolith for protection against solar radiation. Interface modules interconnect the space station modules and can be stacked to provide access to the surface (after Roberts, 1986).

The major advantage of a solar collector system using fiber optics is the savings on electrical power, which is certain to be at a premium on a lunar base. The only power required is that to drive the electric motor that rotates the solar collector toward the sun, which requires less than 1kW. The disadvantages are apparent also, especially is the solar collector remains the sole illumination source. most obvious, no illumination would be provided to the plants during the 14-day-long lunar night. Studies are underway to determine the effects of this lengthy dark period on plant growth (see Rykiel et al., this report), edible biomass production and even survivability, but some degree of detrimental effects can be expected. Of the 21.7 kW of power passed through the emitters, only 42% is absorbed by the plants, leaving 12.6 kW contributing to the latent heat of the chamber, thus requiring large thermal and atmospheric control. The power requirements and energy consumption for this system are summarized in Table 1. Furthermore, current fiber optic technology is such that as much as 35% of light is lost at each junction in the fiber cable, requiring much larger solar collection areas than that described above (Olson et al., 1987).

Table 1. Power and energy requirements for a plant growth chamber 100 m² in area illuminated at full intensity by solar radiation, full intensity by artificial illumination and at low intensity (photosynthetic compensation) by artificial illumination.

	Full Intensity, Solar	Full Intensity, Artificial	Low Intensity, Artificial
Power (kW)			
electricity generation	1.0	108.5	8.2
thermal control	12.6	12.6	1.0
total requirements	13.6	121.1	9.2
Energy consumption			
per day (kJ)	1.18 x 10 ⁶	1.05 x 10 ⁷	7.95 x 10 ⁵

Exclusive Artificial Illumination

Lighting the plant growth chamber exclusively by artificial light eliminates the necessary 14-day light-dark cycle of the lunar day, but the advantages end there. Florescent tubes, Xenon lights and high-intensity discharge (HID) lamps are the three possible lighting candidates. Fluorescent lighting only can be eliminated quickly as being insufficient to attain 750 mE m⁻² sec⁻¹ of the less stringent specifications (Olson et al., 1987). Of the remaining two, HIDs are the more efficient, and produce light at sufficiently high intensities to allow routing the light to plants through fiber optic light pipes, thereby bypassing the heat problem associated with these lamps. The thermal control system is thus simplified.

The power demand is enormous, however. Assuming that HID lights are 20% efficient, approximately 108.5 kW of power must be available to meet illumination requirements inside the chamber.

The 80% of the energy dissipated as sensible heat does not reach the plant chambers because of the fiber optic systems, but the light which does reach the plant growth chambers requires the same 12.6 kW of thermal control as does the solar-exclusive system. Thus it can be estimated that using artificial illumination exclusively will require about 121.1 kW of light generation (Table 1) and thermal control which over a 28-day lunar cycle consumes 2.93×10^{11} Joules of energy.

Solar Illumination with Supplementary Artificial Light

A hybrid system involves the use of solar illumination during the lunar day with artificial lighting during the lunar night. The 14-day long solar period would require some 13.6 kW of power, or a total energy consumption of 1.65×10^{10} Joules. During the 14-day artificial illumination period (lunar night), power requirements increase to the 121.1 kW level. Still, the two systems in tandem require a total energy consumption over a 28-day period of 1.65×10^{11} Joule, or only 56% of the energy consumption if artificial light is used exclusively.

Another alternative is to illuminate the plant chambers during the night cycle by artificial light only at the photosynthetic compensation point, $75 \text{ mE m}^{-2} \text{ sec}^{-1}$ (Olson et al., 1987). The power required to generate this level of illumination is only 8.2 kW and thermal control requirements are reduced to 1.0 kW (Table 1). Low-intensity artificial illumination alternated with full solar illumination thus consumes 2.76×10^{10} Joules of energy, 17% of the full-illumination/solar regime, and only 9.4% of the energy consumption if artificial light at full intensity is used exclusively.

When the need to conserve power is balanced with the intensity and cycling of plant illumination needs, the alternating solar-artificial illumination regime provides the only reasonable alternative. Low-intensity artificial light illumination during the night period provides a significant savings over high-intensity, artificial illumination, but just because the photosynthetic-compensation point is maintained does not mean that plant growth and edible biomass accumulation are maintained. Experiments should be undertaken to compare these two illumination regimes.

PLANT GROWTH IN CHAMBERS

Several potential designs for plant growth chambers (PGCs) have been proposed. The design which appears best to meet criteria for maximizing plant production while minimizing CELSS module mass, power, volume and cost is the "accordion tray" concept (Figure 2) (Oleson and Olson, 1986). The structure of the plant growth trays is more complex than the other types (which will not be discussed here). The accordion trays permit small seeded areas to expand with plant growth, a design which eliminates transplanting.

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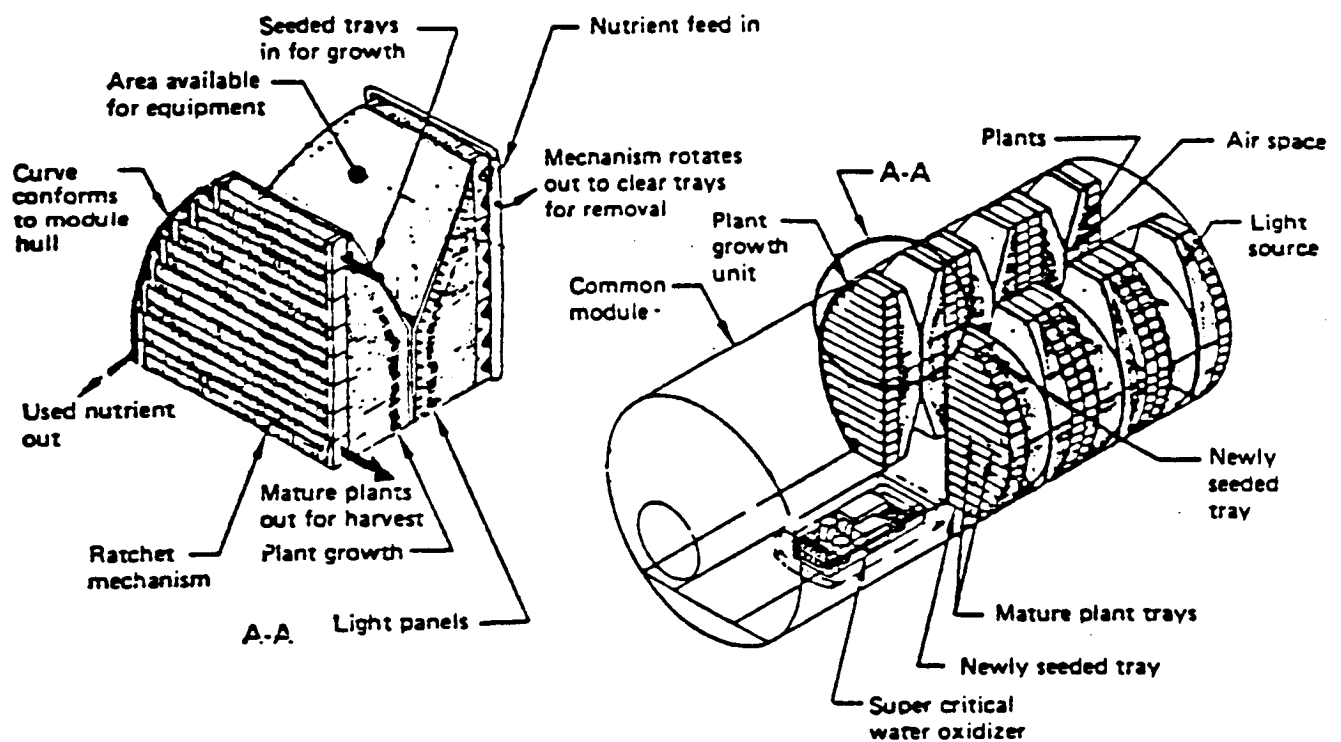


Figure 2. The accordion tray concept fitted into a standard Space Station module. Trays expand to accommodate plant growth and move to wider, center part of hull.

According to the accordion tray concept, there are 24 plant growth units (PGUs) in the PGC. Each unit occupies a volume approximately 76 cm wide by 168 cm high by 142 cm deep. Two PGUs may occupy the floor to ceiling distance, with twelve PGUs on each side of the module. Each PGU has eight trays for plant growth, each tray measuring 20.3 cm square by a maximum of 142.2 cm in length when the accordion bellows are fully extended for mature plants. Overall, a PGU equipped with accordion trays can provide 55.5 m² of plant growth surface area.

When seeds are first placed in the trays, the trays are initially in a collapsed position and inserted at the top-most and bottom-most racks, where the curve of the module hull near floor and ceiling most restricts space. As the plants grow and occupy more volume, the trays are moved into racks toward the center of the module where hull curvature allows for tray expansion. Mature plants ready for harvesting are removed from the center trays.

Water and nutrients are supplied via a nutrient solution (Hoagland's) spray-misted through the trays directly onto the exposed roots. The spray mist system allows root aeration and reduces bulky and massive water requirements.

Table 2 summarizes mass, volume, power requirements and costs for each major subsystem of PGC.

Table 2. Summary of specifications for plant growth chamber using the accordion tray design (from Oleson and Olson, 1986).

PGC System	Qty	Mass (kg)	Volume (m3)	Power (kW)	Cost \$M
PGU	24	704.8	41.2	0.0	22.6
Seeder	1	32.8	0.3	0.2	16.8
Seed cartridges	set	257.0	0.3	0.0	2.0
Nutrient/water supply	1	879.9	1.1	2.2	82.2
Atmospheric control	1	691.0	5.9	6.6	7.4
Harvester	1	465.1	1.3	1.0	49.3
Waste regeneration	1	691.0	1.2	5.6	74.5
Lighting system	1	6062.8	8.1	12.0	167.3
Thermal	1	2106.4	0.9	2.4	24.6
Robots	set	245.8	1.4	0.3	73.2
Total		12136.6	61.7	30.3	519.9

Previous studies of plant productivity using the accordion tray scheme used wheat as a test plant (Oleson and Olson, 1986). Other studies indicate that the white or Irish potato has several advantages over

wheat. Potatoes provide most basic human dietary needs, they have a higher productivity level than wheat and require far less processing into an edible form. Recent studies of intensive cultivation of potatoes (Wheeler and Tibbitts, 1987) under a 24-hour photoperiod achieved sustained yields of $29.4 \text{ g m}^{-2} \text{ day}^{-1}$ on continuous stands. One gram of potato tuber dry matter contains 3.73 kcal (Tibbitts and Alford, 1982), meaning that $110 \text{ kcal m}^{-2} \text{ day}^{-1}$ of food energy can be produced. Assuming a daily caloric requirement of 2800 kcal per human, then approximately 25 m^2 of potatoes are sufficient to provide dietary energy requirements for one person on a continuous basis (Wheeler and Tibbitts, 1987).

With a potential total surface area for plant growth of 55.5 m^2 , a PGC thus has the capacity to produce enough potatoes to feed approximately 2.2 astronauts. For a four-man space station, then, two PGCs are required to meet the crew's dietary needs. Each PGC has a mass of 12,137 kg, which means that an excess of 24,000 kg must be lifted into orbit. The mass of growth chamber per surface area for plant growth is 218.7 kg/m^2 (Table 3).

Table 3. PGC Specifications related to potato cultivation

Mass of PGC (from Table 1)	1213.6	kg
Volume of PGC (from Table 1)	61.7	m^3
Surface area for plant growth in PGC	55.5	m^2
Mass of PGC per surface area for plant growth	218.7	kg m^{-2}
Optimum daily yield of potatoes (1)	29.4	$\text{g m}^{-2} \text{ day}^{-1}$
Energy in tuber dry matter (2)	3.73	kcal g^{-1}
Energy production (1)	110	$\text{kcal m}^{-2} \text{ day}^{-1}$
Caloric needs of one human (1)	2800	kcal
Area of potato cultivation to feed one human (1)	25	m^2
Number of humans sustained per PGC	2.2	
Number of PGCs required for 4-person	2	

1) Wheeler and Tibbitts, 1987

(2) Tibbitts and Alford, 1982

Two PGCs will actually provide some 10% more plant growth capacity than appears necessary to supply four astronauts. Oleson and Olson (1986), in their analysis of PGCs, made provisions for fractionating chambers to minimize space not necessary for growing plants, and thus their calculations indicate that they intend to utilize only about 90% of the PGCs. Fractioning a mere 10% of a plant growth chamber for other purposes, however, seems pointless and potentially hazardous. Cultivating two complete

chambers, thus providing food for an additional "0.4 astronauts" seems wise so as to build up food stores in case of unseen circumstances such as disease outbreak.

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Appendix A

**CONTROLLED ENVIRONMENTAL LIFE
SUPPORT SYSTEMS RESEARCH CONFERENCE**

Prepared by

**F.E. Little
Space Research Center**

**ORIGINAL PAGE IS
OF POOR QUALITY.**

CONTROLLED ENVIRONMENTAL LIFE SUPPORT CONFERENCE

RECON group members participated in several conferences and workshops during this grant period. Foremost among these activities was the two day *Controlled Environmental Life Support Systems Research Conference* at Texas A&M University on February 22 - 23, 1988. The conference was sponsored by The Space Research Center, a Division of the Texas Engineering Experiment Station, part of The Texas A&M University System. The conference featured a keynote address by Ms Peggy Evanich, Program Manager, Propulsion, Power and Energy Division, Office of Aeronautics and Space Technology, NASA Headquarters. In addition to Ms Evanich's address, fifteen technical papers were presented on a wide range of life support topics.

RECON group members contributions to the conference included:

Performance Characterization of a Waste Water Recovery System - Michael Wheeler, Hasan Chowdhury, William Moses, G.P. Peterson and Thomas Rogers

Electrochemical Waste Recycle - Duncan Hitchens

Plant Growth at Low Pressure - Ed Rykiel, Harold Slater and R. D. Spence

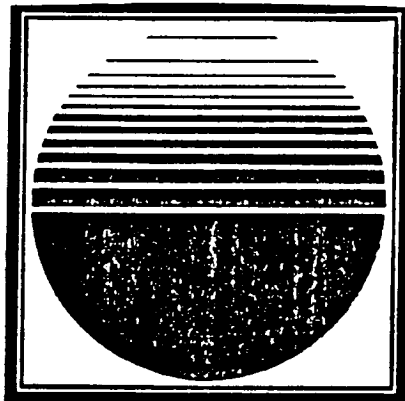
Object-Oriented Model of a Closed Loop Life Support System - Merry Makela, Steve Perkins, A. Dale Whittaker, Heinz Preisig, Mark Holtzapple and Frank Little

Analysis of an Algae-Based CELSS: Part I: Model Development, Part II: Options and Weight Analysis - Mark Holtzapple, Frank Little, Merry Makela, C. O. Patterson and William Moses.

A Complete list of the abstracts and conference registrants follows.

**CONTROLLED ENVIRONMENTAL
LIFE SUPPORT SYSTEMS
RESEARCH CONFERENCE**

ABSTRACTS



February 22-23, 1988

**Space Research Center
Division of Texas Engineering Experiment Station
The Texas A&M University System**

**CONTROLLED ENVIRONMENTAL LIFE SUPPORT
SYSTEMS RESEARCH CONFERENCE**

**Sponsored by
Space Research Center**

The Space Research Center (SRC) was established in 1985 as a cooperative venture between the Texas Engineering Experiment Station (TEES) and NASA Johnson Space Center. The mission of the SRC is to provide a focal point for TAMU research and technology directed toward the scientific and commercial aspects of space. This is accomplished by promoting research, development and applications of knowledge to enhance commercial, state and national benefits from space, and by providing leadership for interdisciplinary activities involving academia, industry and government partnerships.

Regenerative life support systems is one of the research areas of emphasis which is coordinated by the SRC. A unique Regenerative Concepts (RECON) Team has been organized to address the critical issues associated with life support system development. The team includes engineers and scientists experienced in agriculture, agricultural engineering, biology, chemistry, chemical engineering, industrial engineering, and mechanical engineering. The team interacts productively with NASA, industry and university counterparts in a coordinated manner to develop modular concepts for controlled environment systems.

The Controlled Environmental Life Support Systems Research Conference, sponsored by the Regenerative Concepts Team, is offered to members of government, industry and academia in order to present an overview of fundamental research underway at the interdisciplinary level. The field of 16 papers focuses primarily on biologically oriented research, with secondary emphases on physical/chemical processes and system modeling.

CONCEPTUAL DESIGN OF A BREATHABLE AIR PRODUCTION SYSTEM FOR MARS MISSION

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The presence of a manned space colony on Mars may be expected to involve three phases in the utilization of planetary resources: (1) a survival phase in which the basic necessities of life- breathable air, water, and food - are produced, (2) a self-sufficiency phase in which chemicals, fuels, pharmaceuticals, polymers, and metals are produced, and (3) an export to earth of materials and technology phase in which the unique advantage of the extra-terrestrial environment is fully exploited.

The fact that the Martian atmosphere does not have oxygen to support life, has invited engineers to look into means of manufacturing breathable air mixture from the available gas mixture. In this paper the task of conceptual design of the sought system is being discussed. The various phases of project development from data base development, technology review, comparison among various alternatives, components sizing and rating, system synthesis, and energy integration are reviewed.

The project is a part of the NASA/USRA advanced design program's effort to engage engineering students and faculties in the preparation for a Mars Mission. The task dealt with in the College of Engineering at Prairie View A&M University has revealed that several critical technology and engineering design elements require fundamental revisions. Recommendations are made on the future needs, in order to build chemical processing facilities for space applications.

A ROBUST CONTROL STRATEGY FOR UNCERTAIN PLANT GROWTH IN CELSS

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The efficacy of a robust control strategy in regulating the oxygen evolution rate of plants in a bioregenerative life support system has previously been demonstrated by the authors [1]. In utilizing the terminology "robust", we imply that, in the presence of disturbances or uncertainties in parameters or functional forms, stability within a neighborhood of a desired operating point is guaranteed - not merely assured with a certain probability of success. This guarantee of stability is highly desirable for the performance of space systems. These uncertainties describe extraterrestrial growth patterns which may differ from limited data collected in the extraterrestrial environment.

The assumption previously made in developing a robust control strategy was that the growth form of plants was known to be logistics but that uncertainties existed in the parameters of the logistic growth form. Inherent in the assumption of logistic growth is that maximum growth rate per individual occurs at the minimum biomass, whereas environmental conditions may be such that maximum growth rate per individual actually occurs as some later stage of development (depensatory growth). In this case a harvesting strategy based upon the assumption of logistic growth can threaten the stability of the plant population. In this paper we demonstrate how a robust control strategy can be employed to manage the plant growth rate in a CELSS scenario to ensure a stable plant population in the presence of uncertainties in the depensation function form of the plant growth equations.

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**SEED GERMINATION, DEVELOPMENT AND GROWTH OF PLANT TISSUE
CULTURES IN LUNAR SIMULANTS - APPLICATIONS TO CELSS***

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Experiments were carried out on seed germination, development and growth of tissue cultures of several plant genera in the presence of simulated lunar soil (SLS) prepared in the laboratory and on a Minnesota Lunar Simulant which resembles in composition the Apollo 11 lunar rock sample. If plant cells can be grown in such simulants and substrates, their effect on growth and development of plants can be studied and used as base-line data for growing higher plants on a lunar base CELSS. Results on seed germination and seedling growth of rice, corn, tomato, lettuce, tobacco and winged bean and tissue culture of winged bean, soybean, carrot, tobacco, etc. indicate no toxic or inhibitory effects of SLS, although SLS contain high amounts of Aluminum and Chromium compared to earth soil. Since plant tissue culture systems have several advantages (viz., aseptic conditions, well-defined culture media, sensitivity, cloning and propagation), these experiments can play a vital role on lunar-based agriculture, i.e. as part of the bioregenerative life support system, food, landscape and other psychological aspects for future manned missions to the moon, space station and manned interplanetary exploration.

***Research supported by NASA Contract #NAG-9-214, JSC, Houston.
#NASA - Johnson Space Center, Houston, TX 77058**

PERFORMANCE CHARACTERIZATION OF A WASTE/WATER RECOVERY SYSTEM

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This paper describes the experimental evaluation of several of the operating characteristics of a prototype waste/water management system developed in the early 1970's. The experimental procedures initially utilized to characterize the system, the results and conclusions obtained, and the modifications in procedures and equipment required to control the reliability and repeatability of the system operation are discussed.

The system characterization procedure consists of four experiments:

- 1) Determine if a relationship exists between the level of liquid in the evaporator and the power required to drive the paddle motor of the evaporator.**
- 2) While maintaining the evaporator at a constant temperature (100°F), vary the condenser temperature in order to compare the condensation rates.**
- 3) While maintaining the condenser at a constant temperature (60°F), vary the evaporator temperature in order to compare the condensation rates.**
- 4) Determine the mass of water vapor lost through the vacuum pump as a function of system temperature and/or relative condensation rate.**

The primary problem indicated by the initial results was found to be the "slug" flow or boil-over of liquid from the evaporator to the condenser rather than a purely vapor flow in the system. Specific procedures and system modifications to control this problem are discussed in the results. Subsequent testing of the system under the revised experimental procedures has provided effective condensation rates which vary by less than 8% for a series of experiments ranging from one to six hours in total length.

PHOTOELECTROCATALYTIC REDUCTION OF CARBON DIOXIDE

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Reduction of carbon dioxide to organic substances has been carried out in a homogeneous solution, heterogeneous colloidal suspensions and at electrode surfaces. Although the thermodynamic equilibrium potential for the reduction of carbon dioxide to various products is small, the rate of the reaction is slow. For example, the overvoltage for CO_2 reduction is about 2.0 V. It has been proposed that the slow rate is due to the formation of CO_2^- , an intermediate which is involved in the rate determining step. The activation energy for the formation of CO_2^- has been estimated to be 2.5 eV.

Metals deposited on the electrode surface act as catalysts for the reduction process. A systematic study of the effect of catalysts on the photoelectrochemical reduction rate of carbon dioxide is carried out for four different kinds of catalysts-metals, metallophthalocyanines, metal carbonyls and crown ethers. In-situ and ex-situ methods of surface analysis and product distribution results are presented for these systems.

Polarization modulation fourier transform infrared reflection-absorption spectroscopy (PMFTIRRAS) and subtractively normalized interfacial fourier transform spectroscopy (SNIFTIRS) have been applied to the studies of adsorption of crown ethers on p-silicon and gold electrodes in non-aqueous solutions. The potential and concentration dependence of adsorption were observed. 18 - crown - 6 is adsorbed on p - silicon according to a Langmuir isotherm at high concentrations. The introduction of 18 - crown - 6 has catalyzed the photoreduction of CO_2 on p - CdTe in 0.1M TEAP/DMF/5% H_2O , resulting in a shift of the photocurrent-potential relation by c. 410 mV (- 10^3 times increase in the rate constant).

ELECTROCHEMICAL WASTE RECYCLING

**Duncan Hitchens, Texas A&M University
Chemistry Department**

Electrochemical processes will play an important role in the evolution of closed-loop-life support systems. Electrochemical reactors are convenient for use on space missions since they directly utilize electricity to effect chemical transformations and material upgrading.

Technology has been developed to effect "electrochemical incineration" (i.e. complete oxidation) of biomass such as fecal material and inedible plant waste. The main product from the anodic reaction will be CO₂ which is the carbon source for many food regeneration systems and offers a route to oxygen recovery using Bosch or Sabatier reactors. The cathodic reaction yields H₂ which can be recycled as a means of electricity production and water regeneration in fuel cells, thus, the energy costs of the electrolysis can be offset.

Previous work on electrochemistry in waste management will be reviewed including, biochemical fuel cells, urine electrolysis and the use of electrolysis as a provider of nutrients for algae and higher plants.

Experiments on the electrolysis of an artificial fecal slurry will be described in which a single compartment reactor with platinum electrodes was used. Estimates of the current efficiency for CO₂ production from waste will be given. From these experiments, information on both the reaction mechanism and the conditions necessary to maximize the oxidative capabilities of the reactor have been gained.

Experiments using a packed-bed PbO₂ reactor will be described where a batch of waste material can be continuously oxidized using a flow-through system. Lead dioxide surfaces were chosen since they are catalytic towards organic oxidations. Results have shown that additional electron acceptors in the anolyte greatly enhance CO₂ production from organic material.

The implications of this work to the design of practical electrolyzers for CO₂ recovery from waste will be discussed.

DESIGN OF PHOTOMETRIC PROBES FOR STUDYING PLANT PHYSIOLOGY IN MICROGRAVITY

**Oscar Monje
Center for Atmospheric and Space Sciences
University of Utah**

The advent of long term space travel must await the development of a fully operational closed bioregenerative life support system. The feasibility of such a system will depend on the selection of crops capable of meeting both CELSS hardware and productivity level requirements in microgravity. Photometric probes can be used to study plant physiological responses to various environmental stresses, and allow the monitoring of photosynthetic productivity at the molecular level because the parameters they measure are closely associated to reactions mediated by light harvesting pigments. Plant productivity measurements can become criteria for crop selection in future CELSS designs.

There are two main types of photometric techniques: a) fluorescence and b) light transmission. These two configurations and careful selection of the wavelengths of the exciting light and at which measurements are taken provides the ability to obtain data related to several photosynthetic processes. These processes include photosynthetic capacity, electron transfer between photosystems and chlorophyll content. Photometric probes allow the monitoring of the in vivo physiological responses when the sample is exposed to different environmental stresses (ie., temperature, microgravity, humidity, etc.) because the measurements are nondestructive.

The hardware generally consists of a light source, various optical filter combinations, a photodetector, and a microprocessor capable of data acquisition. These probes are very suitable for use in microgravity because they are relatively small, programmable and can be battery powered. Their ability to provide in-flight data circumvents most sample exposure to several g-hours during postflight retrieval.

HUMAN FACTORS IN THE DESIGN FOR A CELSS SYSTEM

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All space craft to date have been designed from the outside in--starting from weight, volume and dimensional limitations and proceeding to the life support, crew systems and human systems. Consequently, these life support and Human Factors systems have been severely constrained by external engineering decisions. Ironically, human performance is determined by crew systems effects on health and productivity. This dilemma suggests that a key to designing long duration space craft and space settlements is to design from the inside out; to begin with optimum crew system, life support and human factors and to consider functional engineering systems from there.

The benefits of Controlled Ecological Life Support Systems (CELSS) promise to be both physical and psychological. The provision of fresh food is both a cargo constraint and a human factor issue: furthermore air and water, natural byproducts of food crops, may supplement mechanically generated life support systems. Human-plant symbiosis, a fact of life on Earth, would also be of enormous psychological value for long duration missions. Reports from Soviet plant experiments in outer space reveal that the cosmonauts felt enormous satisfaction in caring for plants.

In this zero-gravity architectural design for a module on an Earth/Mars crew shuttle, plant growth units have been combined with recreation facilities to insure that humans have daily opportunities to view their gardens. Furthermore, human exercise contributes towards powering the mechanical systems for growing the plants. Although it is in the early stages of development and of uncertain immediate cost-effectiveness, CELSS work affords the most synergetic long term solution to the provision for food, air, water and "homesickness".

CROP GROWTH SYSTEMS FOR THE KENNEDY SPACE CENTER "BREADBOARD" PROJECT¹

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A continuous flow thin film hydroponic nutrient delivery system was chosen initially for growing crops in the Biomass Production Chamber (BPC). It was constructed of polyethylene and polyvinyl chloride plastics. The cylindrical configuration suggested an isosceles trapezoid shaped plant growth tray having an area of 0.25 m². Sixteen trays are provided for each of 4 levels for a total of 64 trays. Polyethylene wings mesh to support the seed and shield the solution from light. A hood or cover serves to maintain almost 100 percent relative humidity during the germinating process. The hood is replaced with a cage which provides the particular crop support throughout its life cycle.

Recent use of 0.2 and 0.5 micron pore size filter materials for growing plants has suggested wider application possibilities. Results of wheat trials on nylon, plastic, and stainless steel filters have shown satisfactory growth. Such systems permit a greater confidence in plumbing since the entire liquid circuit can be confined. These types will be covered along with application into the "Breadboard" Project.

¹ The Kennedy Space Center "Breadboard" Project is part of the Controlled Ecological Life Support system (CELSS) project using the Biomass Production Chamber for control and monitoring plant growth.

PLANT GROWTH AT LOW ATMOSPHERIC PRESSURE

Edward J. Rykiel, Harold H. Slater, Richard D. Spence
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The effects of low atmospheric pressure on higher plant growth were investigated to provide information useful for designing and developing plant growth systems for long-duration space missions and planetary space bases. Survivability and growth responses of radish (*Raphanus sativus*, cult. "Cherry Belle") at 1/20 atmospheric pressure (5 kPa) were compared to those at normal atmospheric pressure (100 kPa) in three types of low pressure chambers, closed system, manually operated open system and automated open system.

In the closed system (no net CO₂ available) radish was able to survive low pressure at least 10 days if illuminated. In darkness plants died quickly because they could neither photosynthesize (no CO₂) nor respire (O₂ partial pressure too low). No net growth could occur because no net CO₂ existed, however, growth resumed when normal pressure was restored and net CO₂ became available.

In the manual open system (net CO₂ available), two chambers were operated at normal pressure (100 kPa) and two at low pressure (5 kPa) with the partial pressures of O₂ and CO₂ in both at approximately 5 kPa and 0.1 kPa respectively. Radish plants increased in biomass throughout an eleven day treatment period, although those at low pressure grew more slowly. Plants in the normal pressure chambers accumulated more biomass than the non-enclosed control (probably because of the higher CO₂ partial pressure of 0.1 kPa vs. 0.035 kPa).

The automated low pressure system has recently been completed and plant growth studies are currently in progress. Current results from this study will be presented.

ANALYSIS OF AN ALGAE-BASED CELSS: MODEL DEVELOPMENT, OPTIONS, AND WEIGHT ANALYSIS

**Mark Holtzapple, Frank Little, William Moses
Comer Patterson, Merry Makela
Texas A&M University**

A CELSS (Controlled Environmental Life Support System) has been developed which incorporates algae for food and oxygen production while physical/chemical processes are used for gas and water regeneration. A stoichiometric model of the process is solved in a sequential, non-iterative manner. The model allows for variations in diet, trash production rate, trash composition, and astronaut metabolism. The accumulation and depletion of components (e.g. H_2 , O_2 , H_2O , CO_2 , food) in storage tanks are determined. The capacity of the various unit operations of the process is calculated so equipment weight may be estimated for trade off analyses. Compared to depleting food stores, the use of algae as food has a "break even" time of 0.9 years; that is, for missions longer than 0.9 years, a weight savings results from the incorporation of algae in the diet.

OBJECT-ORIENTED MODEL OF A CLOSED LOOP LIFE SUPPORT SYSTEM

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An object-oriented simulation model of a closed loop life support system (CELSS) is being developed in LISP using Knowledge Engineering Environment (KEE™) by IntelliCorp, Inc., on a Symbolics 3640 computer. The model consists of two phases: a "shell" and a "configuration". The shell phase (called a generic life support system, GLSS) contains definitions of generic classes of reactors (which include chemical, human, and plant biomass reactors, pumps, mixers, and separators), stores (containing oxygen, hydrogen, carbon dioxide, the crew cabin, water or food) and pipes which connect reactors to stores. The shell also contains routines which facilitate the construction of and help to insure the consistency of a specific configuration. The base configuration currently being constructed consists of four crew members and a crew cabin, an algal biomass reactor for food and O₂ production, the RITE system for waste management and water purification, an electrolysis unit and Bosch reactor for CO₂ reduction and O₂ production, and other assorted reactors and stores. A simulation is run by first specifying the initial conditions of all reactors and stores and then executing the driver routine supplied by the GLSS shell.

HYBRID PLANT/ACTIVATED CHARCOAL FILTER CONTRIBUTION TO ROOM AIR MICROBIAL LOAD

Robert D. Taylor, Elisa Wong, Anne H. Johnson and Billy C. Wolverton¹

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Hybrid air filters of common house plants (*Scindapsus aureus* and *Chlorophytum elatum*) growing over activated charcoal have been demonstrated effective in absorbing gaseous contaminants from room air when this air is fan-forced over the roots of the plants. The air returned to the room is subject to contamination with microflora shed from the roots, soil particles or activated charcoal of the filter, thus investigations of the numbers and types of microorganisms exhausted from the filter are important. Comparisons between a constantly occupied research lab and an infrequently used teaching lab were conducted using both plant filter systems. Viable counts of bacteria, fungi, and actinomycetes were made. Fewer than 100 cfu's/m³ of any of the above microbes were found either in filtered or unfiltered samples in any sampling period and the teaching lab had fewer airborne microorganisms than the research lab. We found that the numbers of microorganisms exhausted from the filters are usually lower than those of unfiltered controls, suggesting that the filters may also serve to remove particulates from room air. Fungal isolates tentatively identified include *Acremonium*, *Aspergillus*, *Cladosporium*, *Montospora*, *Neurospora*, *Nigrospora*, *Paecilomyces*, and *Penicillium*. The bacteria isolated thus far include species of *Achromobacter*, *Azotobacter*, *Bacillus*, *Brevibacterium*, *Escherichia*, *Flavobacterium*, *Pseudomonas*, and several coryneforms. None of the actinomycetes have been identified, but none found have been similar to the nocardias. All isolates are being archived for future study.

POSSIBLE MICROBIOLOGICAL PROBLEMS OF HUMAN-SUPPORTING AGRICULTURAL EXTRA-TERRESTRIAL SYSTEMS

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Because of the possibly catastrophic consequences of plant pathogens attacking plants in human-supporting agricultural systems in extra-terrestrial sites, stringent precautions to prevent the inclusion of any of these pathogens should be taken. The most certain way of avoiding such pathogen inclusion will be to make the plants axenic before they are introduced into the system. Side effects of such use of axenic plants include the elimination of the normal rhizosphere microbiota of the plants. Because these normal microbiota frequently play important protective roles, in their absence, usually non-deleterious micro-organisms, including those which will inevitably be carried by humans into the system, may have unexpected and damaging effects on the plants. Originally axenic *Arabidopsis* populations are being tested for problems of this kind. also under investigation are the possible development of oscillations or chaotic patterns within plant-associated populations of micro-organisms, and the possibility that some "properly" assembled communities of micro-organisms will have stabilizing effects on plant-microbial systems (and some might also have growth-promoting effects on the plants). Current progress in this work will be reported at the Feb. meeting.

ANTARCTIC SUPPORT SYSTEMS AS A MODEL FOR SPACE SUPPORT SYSTEMS

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The present International scientific program in the Antarctic offers a unique opportunity to observe systems that could be used as a Model of systems that will be used in the future for the peaceful development of space. Antarctica is one of the few regions on the face of the globe that cooperation is achieved for the purpose of serving science. The Antarctic treaty has been pointed as a valid starting off point for larger more encompassing treaties. The level of cooperation in the Antarctic has not yet been matched in space research.

The Structure of Antarctic expeditions can be viewed as having three different camp situations. The first category of camp and the most widely experienced is the large year round station such as McMurdo, Scott, and South Pole. The next category of camp is the seasonal station this is not so widely experienced. An example of this type of camp would be the presently deactivated Beardmore Station. The third category of camp is the field party. This type of camp is the most rigorous and rarest type of support system presently employed in the Antarctic. It is my opinion that this offers a clear model of how space will be developed using this three tier system presently used in the antarctic as a Model. It has even been noted that the actual structures of Martian bases would be similar to Antarctic Bases such as South Pole. The conditions of Social and Sensory deprivation provide an excellent opportunity to see exactly how psychological adaptation occurs in an extreme environment situation.

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Appendix B
DETAILS OF STEADY STATE MODEL

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Appendix B

Details of Steady State Model

Model Development

Figure 1 shows a schematic representation of a CELSS approach which incorporates plants or algae to supplement the diet of the astronauts. Reactors are represented as square boxes, separators as circles, and storage tanks as rounded boxes. Table 1 indicates the composition of each stream. Many of the streams have well defined chemical compositions (e.g., H_2 , O_2 , CO_2 , N_2 , H_2O , and NH_3) while some of the streams are not well defined (e.g., edible plants, inedible plants, food, feces, urine, trash.)

A stoichiometric model of the CELSS system shown in Fig. 1 is necessary to define the capacities of the various reactors and separators. These capacities allow sizing of the components for weight, volume, and power trade-off studies. Also, the stoichiometric model will allow the daily accumulation (or depletion) of each of the tanks to be calculated. It will then be possible to determine if certain components must be supplied or if there will be a net production of some chemicals which may be used for other purposes. To be useful the stoichiometric model must allow for various compositions of food and trash. There will be no attempt to model the system exactly since this would be too cumbersome. Instead, the stoichiometric model will be a "first-order" analysis of the system which sacrifices some accuracy in favor of simplicity. As with all models, some assumptions must be made.

The algae, food, and feces are assumed to be composed of carbohydrate, protein, fat, and fiber. Although there is an ash component in each of these items, the ash is inert so it is neglected in this first-order analysis. Table 2 shows the assumed chemical formulae and energy content for carbohydrates, protein, fat, and fiber, and lignin.

Urine contains about 60% organic substances (e.g., urea, uric acid, creatinine, and ammonia) and 40% inorganic salts.¹⁷ For simplicity, the salt fraction will be considered inert and will be neglected. The organic fraction is assumed to be urea which is derived from ingested protein.

The trash contains a number of items such as waste paper, plastic wrappings and food scraps. It is assumed that metallic items have not been deposited in the trash, since they may foul the waste treatment process. It will be assumed that all the trash sent to the combustor will consist of C, H, O, and N atoms. Although there are plastics which contain S and Cl, it is assumed that these may not be allowed in the spacecraft or that they will not be burned in the combustor since the combustion products of these elements may be dangerous.

The chemical reactions occurring in each of the reactors of Fig. 1 are shown in Table 3. In the waste combustor, some oxides of nitrogen (NO_x) would be formed. It is assumed that the exit gases from the

combustor are passed through a catalyst which decomposes the NO_x to N_2 and H_2O by the addition of ammonia.¹⁸ Since the NO_x yields are unknown, the ammonia required for its elimination cannot be calculated and hence is ignored.

Although a number of control strategies may be devised to regulate the operation of the chemical reactors, the strategy shown in Table 4 was designed to minimize the capacity of each reactor. For example, the Bosch reactor could operate at higher than the minimum rate required to meet the water needs and produce more water which could then be split to produce extra oxygen. This would make the equipment larger than necessary for achieving the basic water balance and increase power consumption.

The food eaten by the astronauts is composed of plants or algae plus items from the food stores. Tables 5, 7 and 11 show the method for determining the total composition of the food eaten by the astronauts. Table 6 lists the composition of some food items which might be used to supplement the plant/algal diet. Tables 8 and 9 show the method for calculating the composition of plant residues and Table 10 shows the method for calculating the composition of the entire plant. The elemental composition of the trash is calculated as shown in Table 12. The generalized chemical formula for trash is $\text{CH}_a\text{O}_b\text{N}_c$. Table 12 also shows how the constants a, b, and c are calculated.

With the preliminary information described thus far, it is possible to calculate the flow rates, R, of the various process streams and the accumulation, A, or depletion, D, of materials in the various tanks. The procedure for making these calculations will be presented in a stepwise manner. When the calculations are performed in the following order, there is no need for trial-and-error solutions to a series of simultaneous equations; that is, this system of equations can be solved in a sequential, stepwise manner. Most of these equations were developed using simple material balances around each of the pieces of equipment shown in Figure 1.

1. Energy content of food

The energy content of food is commonly measured in kcal/g. This is converted to J/g using the conversion factor of 4190.

$$E = (4C_t + 4P_t + 9F_t) 4190 = 16,760 C_t + 16,760P_t + 37,710F_t \quad (1)$$

2. Rate of food metabolism

The food required for metabolism is easily calculated from the energy content of the food. The conversion factor 86.4 is required to convert g/s to kg/d.

$$R_{\text{food,met}} = \frac{M}{E} 86.4 \quad (2)$$

Table 13 lists some metabolic heats for various activities.

3. Rate of CO₂ production by metabolism

The components of $R_{\text{food,met}}$ which can be metabolized (carbohydrate, protein and fat) are converted to carbon dioxide according to the following relationship

$$\begin{aligned} R_{\text{CO}_2}^{\text{met}} &= \left(\frac{6(44)}{180} C_t + \frac{3.5(44)}{83} P_t + \frac{16(44)}{256} F_t \right) R_{\text{food,met}} \\ &= (1.467 C_t + 1.855 P_t + 2.75 F_t) R_{\text{food,met}} \end{aligned} \quad (3)$$

4. Rate of O₂ consumption by metabolism

The amount of oxygen required to metabolize the food is given by

$$\begin{aligned} R_{\text{O}_2}^{\text{met}} &= \left(\frac{6(32)}{180} C_t + \frac{4(32)}{83} P_t + \frac{23(32)}{256} F_t \right) R_{\text{food,met}} \\ &= (1.067 C_t + 1.542 P_t + 2.875 F_t) R_{\text{food,met}} \end{aligned} \quad (4)$$

5. Rate of H₂O production by metabolism

The rate of water production by metabolism is given by

$$\begin{aligned} R_{\text{H}_2\text{O}}^{\text{met}} &= \left(\frac{6(18)}{180} C_t + \frac{1.5(18)}{83} P_t + \frac{16(18)}{256} F_t \right) R_{\text{food,met}} \\ &= (0.6 C_t + 0.325 P_t + 1.125 F_t) R_{\text{food,met}} \end{aligned} \quad (5)$$

6. Rate of urea production by metabolism

Urea is produced by the metabolism of proteins.

$$R_{\text{urea}}^{\text{met}} = \frac{0.5(60)}{83} P_t R_{\text{food,met}} = 0.361 P_t R_{\text{food,met}} \quad (6)$$

7. Rate of food consumption

The rate at which food is consumed is larger than the rate of food which is metabolized. A portion of the food is fiber and exits in the feces. (See Table 14 for the composition of feces.) The human small intestine is not able to recover all the nutrients in the food since some of them are adsorbed onto the fiber. Some of these nutrients are utilized by microbes in the latter part of the large intestine. Also, some of the protein and fat is nondigestible and exits in the feces. Some fat also sluffs off of the intestinal lining. Thus, it can be seen that the digestion process is very complex. For this first-order analysis, it

will be assumed that the food consumed can be partitioned into two fractions of identical composition (see Figure 2). The first fraction of the food is used for metabolism ($R_{\text{food,met}}$) and the other fraction ($R_{\text{food,feces}}$) results in feces production. The fiber fraction of $R_{\text{food,met}}$ also will ultimately end up in the feces. The ratio, r , will be defined as the amount of nonfibrous fecal matter to the fibrous fecal matter

$$r = \frac{\text{nonfibrous fecal matter}}{\text{fibrous fecal matter}}$$

For simplicity, this ratio is calculated on a mineral-free basis and is assumed to be constant. From the data shown in Table 14, a typical value is $r=1.583$. Examination of Figure 2 shows that the ratio r may be written explicitly as

$$r = \frac{(1 - B_t) R_{\text{food, feces}}}{B_t R_{\text{food, cons}}}$$

This may be solved for $R_{\text{food,feces}}$. The ratio, s , is defined as the ratio of food consumed to food eaten for metabolism

$$s = \frac{R_{\text{food, cons}}}{R_{\text{food, met}}}$$

This may be solved for $R_{\text{food,met}}$. The total food consumed is the sum of food used for metabolism and the food used for feces production

$$R_{\text{food, cons}} = R_{\text{food, met}} + R_{\text{food, feces}}$$

Substituting expressions for $R_{\text{food,met}}$ and $R_{\text{food,feces}}$ and solving for s gives

$$s = \frac{1 - B_t}{1 - (1 + r)B_t} \quad (7)$$

This value of s may then be used to calculate the food consumed from the food metabolized

$$R_{\text{food, cons}} = s R_{\text{food, met}} \quad (8)$$

It should be noted that Equation 7 has a singularity when $(1+r)B_t=1$ and that s is negative when $(1+r)B_t > 1$. This results from the assumption that r is a constant. In actuality, r is a function of B_t . This

functional relationship is not known, so the assumption that it is constant is used as a starting point. Further refinement will require experimental feeding trials.

8. Rate of feces production

The feces are composed of fibrous and nonfibrous matter. The rate of fecal production can be calculated from

$$R_{feces} = (1 + r) B_i R_{food, cons} \quad (9)$$

9. Rate of water loss in breath

During the act of breathing, air is brought into the lungs, where it is heated to body temperature and becomes saturated with moisture. The rate at which water evaporates from the lungs, $R_{breathing}$, is given by

$$R_{breathing} = Q (g_{out} - g_{in})$$

where Q is the volumetric flow of air through the lungs and g is the water content of the air going into and coming out of the lungs. The volumetric flow of air is related to the metabolic rate of the astronaut. A man at rest (118W) breathes about 18 breaths per minute with a volume of 0.75 L per breath.^{19,20} This translates to 19,400 L/d of air. Guyton³¹ gives figures of 12 breaths per minute and 0.5 L per breath which translates to 8,640 L/d. We have chosen the higher estimate as a more conservative approach in estimating the required size of the water separator. Assuming the breathing rate is linear with metabolic rate, the breathing rate for other metabolic rates is given by

$$Q = 164 M$$

The water content of air is given by

$$g = \frac{p^{vap}}{RT} 18 \phi$$

where p^{vap} is the vapor pressure of water at temperature T . The parameter ϕ is the relative humidity of the air expressed as a fraction which varies from 0 to 1.

An empirical expression for the vapor pressure of water is

$$p^{vap} = B - \frac{A}{C + t}$$

where p^{vap} is in mm Hg and t is in °C. The constants are $A = 1750.286$ °C, $B = 8.10765$, and $C = 235.0$ °C.

Substituting the above expressions, g may be calculated as

$$g = \frac{8.10765 - \frac{1750.286}{235.0 + t}}{10} \quad 18 \phi = \frac{8.10765 - \frac{1750.286}{235.0 + t}}{t + 273.15} \quad 0.2886 \phi$$

$$\left(0.08205 \frac{\text{atm L}}{\text{gmole } ^\circ\text{K}} \right) \left(760 \frac{\text{mmHg}}{\text{atm}} \right) (t + 273.15)$$

The air exiting the lungs is assumed to be saturated with moisture (i.e., $\phi = 1$) at 37°C. Therefore, it has a water content g_{out} of 0.0438g/L. The water content of the air entering the lungs is dependent on the cabin temperature and relative humidity. The water loss by breathing, $R_{breathing}$ (in kg/day), is given by

$$R_{breathing} = 0.164M \left(0.0438 - 0.2886 \frac{10}{t + 273.15} \phi \right) \quad (10)$$

10. Rate of urine water produced

The sources of water for an astronaut are the water he drinks, the water produced from the metabolism of food, and the water in the food he eats. The astronaut loses water in urine, by sweating, in his breath, and in his feces. An expression for urine water may be obtained as follows:

$$R_{urine} = R_{drink} + R_{H_2O}^{met} + w_{food} R_{food,cons} - R_{sweat} - R_{breathing} - w_{feces} R_{feces} \quad (11)$$

where w_{food} is the ratio of food water to dry food and w_{feces} is the ratio of fecal water to dry feces.

11. Rate of water production in combustor

The combustor burns trash, urea from urine, and feces according to the stoichiometries shown in Table 3. The rate of water production for each component is shown below.

a. trash

$$R_{H_2O,a}^{comb} = \frac{\frac{a}{2}(18)}{12 + a + 16b + 14c} R^{trash} \quad (12)$$

b. urea

$$R_{H_2O,b}^{comb} = \frac{2(18)}{1(60)} R_{urea}^{met} = 0.6 R_{urea}^{met} \quad (13)$$

c. fecal fiber

$$R_{H_2O,c}^{comb} = \frac{5(18)}{1(162)} B_t R_{food,cons} = 0.555 B_t R_{food,cons} \quad (14)$$

d. fecal fat

$$R_{H_2O,d}^{comb} = \frac{16(18)}{1(256)} B_t F_f R_{food,cons} = 1.125 B_t F_f R_{food,cons} \quad (15)$$

where F_f is the ratio of fecal fat to fecal fiber.

e. fecal protein

$$R_{H_2O,e}^{comb} = \frac{2.5(18)}{1(83)} B_t F_p R_{food,cons} = 0.542 B_t F_p R_{food,cons} \quad (16)$$

where F_p is the ratio of fecal protein to fecal fiber.

f. fecal cells

$$R_{H_2O,f}^{comb} = \frac{0.833(18)}{1(20.786)} B_t F_c R_{food,cons} = 0.721 B_t F_c R_{food,cons} \quad (17)$$

where F_c is the ratio of fecal cells to fecal fiber.

g. plant wastes

$$R_{H_2O, g}^{comb} = \frac{0.5np_x (18)}{12 + np_x + 16np_y + 14np_z} PW (1 - x_{foodstores}) R_{food, cons} \quad (18)$$

The total water output from the combustor includes the water from the reactions calculated above and the water which enters with some of the food materials.

$$R_{H_2O}^{18} = R_{H_2O, a}^{comb} + R_{H_2O, b}^{comb} + R_{H_2O, c}^{comb} + R_{H_2O, d}^{comb} + R_{H_2O, e}^{comb} + R_{H_2O, f}^{comb} + R_{H_2O, g}^{comb} + w_{trash} R_{trash} + w_{feces} R_{feces} + NPW_t (1 - x_{foodstores}) R_{food, cons} PW \quad (19)$$

where w_{trash} is the ratio of water in trash to the dry trash.

12. Rate of carbon dioxide production in the combustor

The reaction stoichiometries shown in Table 3 may be used to calculate the CO_2 production in the combustor.

a. trash

$$R_{CO_2, a}^{comb} = \frac{44}{12 + a + 16b + 14c} R_{trash} \quad (20)$$

b. urea

$$R_{CO_2, b}^{comb} = \frac{1(44)}{1(60)} R_{urea}^{met} = 0.733 R_{urea}^{met} \quad (21)$$

c. fecal fiber

$$R_{CO_2, c}^{comb} = \frac{6(44)}{1(162)} B_t R_{food, cons} = 1.630 B_t R_{food, cons} \quad (22)$$

d. fecal fat

$$R_{CO_2, d}^{comb} = \frac{16(44)}{1(256)} B_t F_f R_{food, cons} = 2.75 B_t F_f R_{food, cons} \quad (23)$$

e. fecal protein

$$R_{CO_2}^{comb} = \frac{4(44)}{1(83)} B_{tP} R_{food,cons} = 2.12 B_{tP} R_{food,cons} \quad (24)$$

f. fecal cells

$$R_{CO_2}^{comb} = \frac{1(44)}{1(20.786)} B_{tF_c} R_{food,cons} = 2.117 B_{tF_c} R_{food,cons} \quad (25)$$

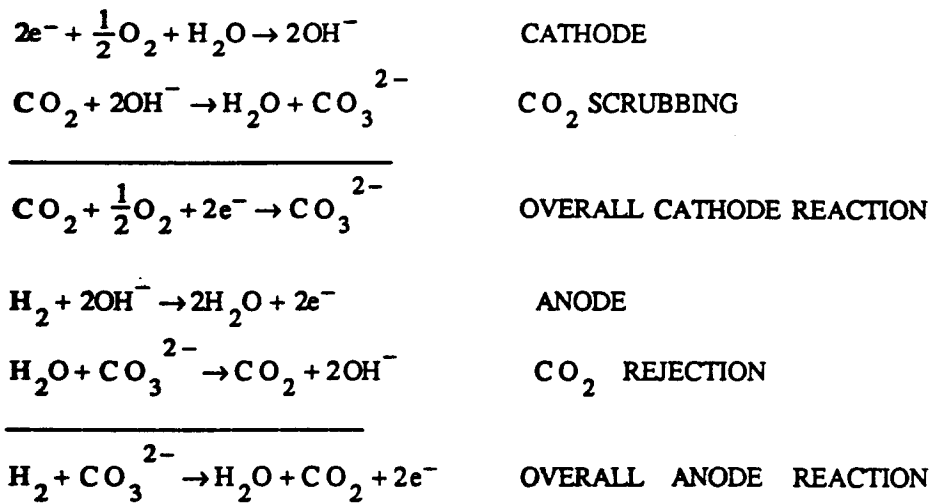
g. plant waste

$$R_{CO_2}^{comb} = \frac{1(44)}{12 + np_x + 16np_y + 14np_z} PW (1 - x_{foodstores}) R_{food,cons} \quad (26)$$

The total carbon dioxide production from the combustor will be the sum of the above rates

$$R_{CO_2}^{18} = R_{CO_2}^{comb,a} + R_{CO_2}^{comb,b} + R_{CO_2}^{comb,c} + R_{CO_2}^{comb,d} + R_{CO_2}^{comb,e} + R_{CO_2}^{comb,f} + R_{CO_2}^{comb,g} \quad (27)$$

Carbon dioxide may be removed from the cabin atmosphere by an electrochemical depolarizer. The electrochemical depolarizer is essentially a fuel cell which allows carbon dioxide to be transferred from one electrode to another. It has the following stoichiometry.



The following equations must be used if the electrochemical depolarizer is used:

$$R_{H_2}^{32} = \frac{1(2)}{1(44)} \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) = 0.04545 \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) \quad (28)$$

$$R_{O_2}^{34} = \frac{0.5(32)}{1(44)} \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) = 0.3636 \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) \quad (29)$$

$$R_{H_2O}^{33} = \frac{1(18)}{1(44)} \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) = 0.409 \left(R_{C O_2}^{met} + R_{C O_2}^{18} \right) \quad (30)$$

If a purely physical method, such as a membrane, is used to separate CO₂, then the above rates would be zero

$$R_{H_2}^{32} = 0 \quad (28')$$

$$R_{O_2}^{34} = 0 \quad (29')$$

$$R_{H_2O}^{33} = 0 \quad (30')$$

13. Oxygen required for combustion

The reaction stoichiometries shown in Table 3 allow the oxygen required for combustion to be calculated.

a. trash

$$R_{O_2,a}^{comb} = \frac{\left(1 + \frac{a}{4} - \frac{b}{2}\right)(32)}{12 + a + 16b + 14c} R_{trash} \quad (31)$$

b. urea

$$R_{O_2,b}^{comb} = \frac{1.5(32)}{1(60)} R_{urea}^{met} = 0.8 R_{urea}^{met} \quad (32)$$

c. fecal fiber

$$R_{O_2,c}^{comb} = \frac{6(32)}{1(162)} B_t R_{food,cons} = 1.185 B_t R_{food,cons} \quad (33)$$

d. fecal fat

$$R_{O_2, d}^{comb} = \frac{23(32)}{1(256)} B_t F_f R_{food, cons} = 2.875 B_t F_f R_{food, cons} \quad (34)$$

e. fecal protein

$$R_{O_2, e}^{comb} = \frac{4.75(32)}{1(83)} B_t F_p R_{food, cons} = 1.831 B_t F_p R_{food, cons} \quad (35)$$

f. fecal cells

$$R_{O_2, f}^{comb} = \frac{1.282(32)}{1(20.786)} B_t F_c R_{food, cons} = 1.974 B_t F_c R_{food, cons} \quad (36)$$

g. plant waste

$$R_{O_2, g}^{comb} = \frac{(1 + \frac{npz}{4} - \frac{npz}{2})32}{12 + npz + 16npz + 14npz} PW (1 - x_{foodstores}) R_{food, cons} \quad (37)$$

The total oxygen required is determined by summing the above equations

$$R_{O_2}^{19} = R_{O_2, a}^{comb} + R_{O_2, b}^{comb} + R_{O_2, c}^{comb} + R_{O_2, d}^{comb} + R_{O_2, e}^{comb} + R_{O_2, f}^{comb} + R_{O_2, g}^{comb} \quad (38)$$

14. Rate of water removal by the water remover

In order to prevent a build-up of moisture in the cabin, the water remover must remove the water produced by breathing, sweating, and combustion of wastes.

$$R_{H_2O}^{12} = R_{breathing} + R_{sweat} + R_{H_2O}^{18} \quad (39)$$

15. Plant/Algal growth chambers

The stoichiometry of plant growth is shown in Table 3. Each component will be considered in sequence.

a. carbon dioxide consumption

$$R_{CO_2}^9 = \frac{1(44)}{12 + px + 16py + 14pz} (1 - x_{foodstores}) R_{food, cons} (1 + PW) \quad (40)$$

b. water consumption

$$R_{H_2O}^{20} = \frac{(0.5px - 1.5pz)18}{12 + px + 16py + 14pz} (1 - x_{\text{foodstores}}) R_{\text{food,cons}} (1 + PW) + NPW_i (1 - x_{\text{foodstores}}) R_{\text{food,cons}} PW + EPW_i (1 - x_{\text{food stores}}) R_{\text{food,cons}} \quad (41)$$

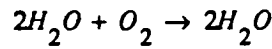
c. ammonia consumption

$$R_{NH_3}^{29} = \frac{17pz}{12 + px + 16py + 14pz} (1 - x_{\text{foodstores}}) R_{\text{food,cons}} (1 + PW) \quad (42)$$

d. oxygen production

$$R_{O_2}^8 = \frac{(1 + 0.25px - 0.75pz - 0.5py)32}{12 + px + 16py + 14pz} (1 - x_{\text{foodstores}}) R_{\text{food,cons}} (1 + PW) \quad (43)$$

The nitrogen required for the synthesis of ammonia may be separated from oxygen by reacting away the oxygen by combusting it with hydrogen



The following equations are used if this method of nitrogen separation is used.

$$R_{H_2}^{35} = \left(\frac{2(2)}{1(32)} \right) \left(\frac{0.21(32)}{0.79(28)} \right) \left(\frac{1(28)}{2(17)} \right) R_{NH_3}^{29} = 0.03127 R_{NH_3}^{29} \quad (44)$$

$$R_{O_2}^{\text{nitrogensep}} = \left(\frac{0.21(32)}{0.79(28)} \right) \frac{1(28)}{2(17)} R_{NH_3}^{29} = 0.2502 R_{NH_3}^{29} \quad (45)$$

$$R_{H_2O}^{36} = \frac{2(18)}{1(32)} \left(\frac{0.21(32)}{0.79(28)} \right) \frac{1(28)}{2(17)} R_{NH_3}^{29} = 0.2815 R_{NH_3}^{29} \quad (46)$$

If a purely physical method (such as membranes) is employed, then the above rates are equal to zero

$$R_{H_2}^{35} = 0 \quad (44')$$

$$R_{O_2}^{nitrogensep} = 0 \quad (45')$$

$$R_{H_2O}^{36} = 0 \quad (46')$$

16. Electrolyzer

The electrolyzer produces both oxygen and hydrogen. The required capacity of the electrolyzer will be determined by which demand is greater. If the demand for oxygen is greater (i.e., oxygen control), then an excess of hydrogen will be produced. If the demand for hydrogen is greater (i.e., hydrogen control), then there will be an excess of oxygen produced. Assuming that the electrolyzer is controlled by the oxygen demand, the following analysis is used. If this assumption is in error, the hydrogen storage tank would have to be depleted in order to supply the excess demand for hydrogen.

a. oxygen production

The electrolyzer must produce oxygen for human metabolism and waste combustion. The plant/algae reactor will supplement this requirement.

$$R_{O_2}^5 = R_{O_2}^{met} + R_{O_2}^{19} - R_{O_2}^8 + R_{O_2}^{34} + R_{O_2}^{nitrogensep} \quad (47)$$

b. hydrogen production

$$R_{H_2}^{30} = \frac{2(2)}{1(32)} R_{O_2}^5 = 0.125 R_{O_2}^5 \quad (48)$$

c. water consumption

$$R_{H_2O}^3 = \frac{2(18)}{1(32)} R_{O_2}^5 = 1.125 R_{O_2}^5 \quad (49)$$

17. Bosch Reactor

a. water production

According to the control strategy described in Table 4, the Bosch reactor will produce only enough water to prevent the level in the water tanks from being depleted. The depletion in the water tanks, is found by performing a balance around the tank.

$$D_{H_2O} = OUT - IN$$

$$D_{H_2O} = R_{H_2O}^3 + w_{food} R_{food,cons} + R_{H_2O}^{20} + R_{drink} - R_{urine} - R_{H_2O}^{12} - R_{H_2O}^6$$

The condition that the depletion is zero allows the water produced by the Bosch reactor to be calculated

$$R_{H_2O}^6 = R_{H_2O}^3 + R_{H_2O}^{20} + R_{drink} - R_{urine} - R_{H_2O}^{12} - R_{H_2O}^{33} - R_{H_2O}^{36} \quad (50)$$

This formula is subject to the condition that $R_{H_2O}^6$ would not go negative. If it does go negative, then $R_{H_2O}^6 = 0$.

b. carbon production

$$R_C^{28} = \frac{1(12)}{2(18)} R_{H_2O}^6 = 0.3333 R_{H_2O}^6 \quad (51)$$

c. hydrogen consumption

$$R_{H_2}^4 = \frac{2(2)}{2(18)} R_{H_2O}^6 = 0.1111 R_{H_2O}^6 \quad (52)$$

d. carbon dioxide consumption

$$R_{CO_2}^7 = \frac{1(44)}{2(18)} R_{H_2O}^6 = 1.2222 R_{H_2O}^6 \quad (53)$$

18. Ammonia Synthesizer

a. ammonia production

The ammonia synthesizer must fix the nitrogen for the plants/algae. It will be assumed that it will produce only the amount of ammonia required so a storage tank is not required.

$$\overset{\text{ammonia synthesizer}}{R_{NH_3}} = R_{NH_3}^{29} \quad (54)$$

b. hydrogen requirement

$$R_{H_2}^{25} = \frac{3(2)}{2(17)} R_{NH_3}^{29} = 0.176 R_{NH_3}^{29} \quad (55)$$

19. Storage tanks

The various tanks have inputs and outputs. If inputs are greater than outputs, the tank will accumulate material. If the outputs are greater than the inputs, the tank will lose material.

a. hydrogen accumulation

$$A_{H_2} = R_{H_2}^{30} - R_{H_2}^4 - R_{H_2}^{25} - R_{H_2}^{32} - R_{H_2}^{35} \quad (56)$$

b. carbon dioxide accumulation

The carbon dioxide tank is supplied with carbon dioxide from metabolism and waste combustion and is depleted by the algae reactor and Bosch reactor.

$$A_{CO_2} = R_{CO_2}^{met} + R_{CO_2}^{18} - R_{CO_2}^9 - R_{CO_2}^7 \quad (57)$$

c. water accumulation

$$A_{H_2O} = R_{H_2O}^{12} + R_{urine}^6 + R_{H_2O}^6 - R_{H_2O}^3 - R_{H_2O}^{20} - R_{drink} + R_{H_2O}^{33} + R_{H_2O}^{36} \quad (58)$$

Typically, $A_{H_2O} = 0$ since the Bosch reactor rate $R_{H_2O}^6$ is adjusted so the tank level stays constant.

d. oxygen accumulation

It has been assumed that the oxygen production requirements control the electrolyzer. In this case, the production rate is regulated so there is no accumulation of oxygen in the tank

C-4

$$A_{O_2} = 0 \quad (59)$$

If this assumption were wrong, it would cause A_{H_2} to be negative. For the case of a hydrogen-controlled electrolyzer, it would be necessary to implement a control strategy where the electrolyzer is regulated so there is no accumulation of hydrogen in the storage tank. In this case, oxygen would accumulate in its storage tank.

e. food depletion

Any food consumption not met by plants/algae must be met by depleting the food stores

$$D_{food} = x_{foodstores} R_{food,cons} \quad (60)$$

Calculational Procedure

The required capacity for each of the reactors and separators and the level of each of the tanks may be calculated by the following procedure:

1. Specify independent inputs

Typical values of the independent inputs are listed below:

- a. metabolic rate²¹ = 135 W/man
- b. trash production rate²¹ = 0.818 kg/man d
- c. cabin temperature = 21°C
- d. cabin relative humidity = 0.3
- e. drink rate²¹ = 1.3 kg/man d
- f. sweat rate²¹ = 0.918 kg/man d

2. Specify physical relations

- a. $r = 1.583^{22}$
- b. $F_f = 0.5^{22}$
- c. $F_p = 0.0833^{22}$
- d. $F_c = 1^{22}$
- e. $w_{feces} = 3^{22}$
- f. $w_{trash} = 0.1$

3. Calculate composition of food store items- see Table 5

4. Calculate composition of edible plants - see Table 7

5. Input residue coefficients - see Table 8

6. Calculate composition of nonedible plant residue - see Table 9

7. Calculate composition of entire plant - see Table 10

8. Calculate composition of food eaten - see Table 11
9. Calculate elemental composition of trash - see Table 12
10. Calculate equations 1 to 60 sequentially

(Note: equation 50 is subject to the condition that it not go negative. If it does,

$$R_{H_2O}^6 = 0 .)$$

11. Report results

Conclusions

A "stoichiometric model" has been presented which calculates the required capacities of each unit operation in a CELSS which incorporates plants/algae and chemical methods to process air and wastes. Most of the equations in the model are linear. The equations may be solved sequentially rather than simultaneously which makes it easy to implement in a computer program.

The model is driven primarily by the human metabolic rate; therefore, it may be used to determine the effect of astronaut exercise levels on the required capacity of each unit operation in the CELSS. This is important if exercise is used to counter the adverse effects of low gravity on humans.

The first-order model presented in this paper is not an exact representation of reality. The major simplification of the model is the manner in which food is divided into fractions which are used for metabolism and feces production. The model assumes that nonfiber fractions allocated to metabolism are completely metabolized. This is not completely correct since some food components (e.g., protein and fat) cannot be completely metabolized, some would end up in the feces. Also, the non-fiber food fraction allocated to feces production is assumed to be completely transformed into microbes. This is a gross simplification since some of the most readily available fractions (e.g., carbohydrate) would be used by human metabolism. Another simplification was that the composition of the feces was independent of the food composition. This simplifying assumption can lead to mismatches in elemental composition between the food allocated for feces production and the actual feces composition. Thus the model may not predict closure when in fact closure would be possible. The errors caused by the simplifying assumptions are relatively minor. The model should give reasonable approximations to reality except in the case of very high fiber diets.

Nomenclature

- A = accumulation kg/d
- a = molar ratio of hydrogen to carbon in trash, dimensionless
- B = fiber, mass fraction
- b = molar ratio of oxygen to carbon in trash, dimensionless

C = carbohydrate, mass fraction
c = molar ratio of nitrogen to carbon in trash, dimensionless
D = depletion, kg/d
E = energy content of food, J/g
F = fat, mass fraction
F_C = ratio of fecal cells to fecal fiber, dimensionless
F_f = ratio of fecal fat to fecal fiber, dimensionless
F_p = ratio of fecal protein to fecal fiber, dimensionless
g = water content of air, g/L
M = metabolic rate, W
P = protein, mass fraction
p^{vap} = vapor pressure of water, mmHg
Q = volumetric breathing rate, L/d
R = rate, kg/d
R = universal gas constant, 0.08205 atm L/gmole °K
r = ratio of nonfibrous fecal matter to fibrous fecal matter, dimensionless
s = ratio of total food consumed to food for metabolism, dimensionless
T = absolute temperature, °K
t = temperature, °C
TC = trash carbon, mass fraction
TH = trash hydrogen, mass fraction
TO = trash oxygen, mass fraction
TN = trash nitrogen, mass fraction
w = ratio of water to dry solids, dimensionless
x = fraction of total food eaten, mass fraction
y = fraction of total trash, mass fraction
φ = relative humidity, fraction (NOT percent)

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Table 1. Composition of the streams shown in Figure 1.

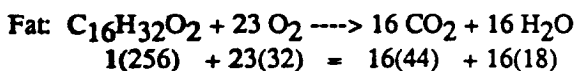
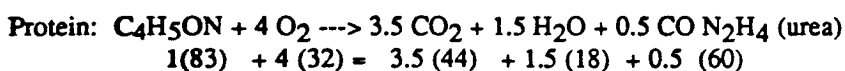
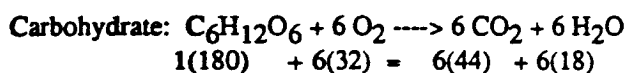
Stream	H ₂	O ₂	CO ₂	N ₂	H ₂ O	C	NH ₃	Edible Plants (Dry)	Food (Dry)	Feces (Dry)	Urine (Dry)	Trash (Dry)	Inedible Plants (Dry)
1					x						x		
2					x								
3					x								
4	x												
5		x											
6					x								
7			x										
8		x											
9			x										
10					x			x					
11		x	x	x	x								
12					x								
13		x		x									
14					x				x				
15		x											
16					x					x			
17					x							x	
18			x	x	x								
19		x											
20					x								
21		x	x	x									
22			x										
23					x								
24													x
25	x												
26				x									
27		x		x									
28						x							
29							x						
30	x												
31											x		
32	x												
33					x								
34		x											
35	x												
36					x								

Table 2. Chemical formulae for carbohydrate, protein, fat, fiber, and lignin.³²

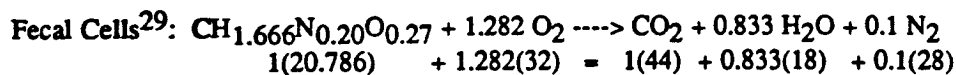
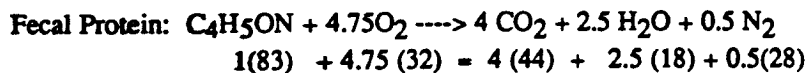
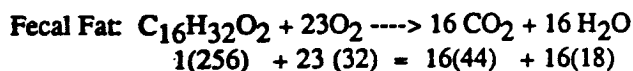
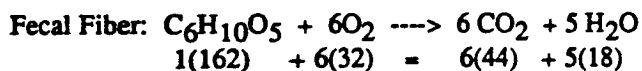
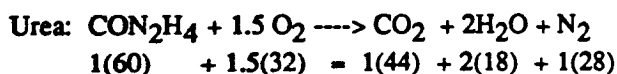
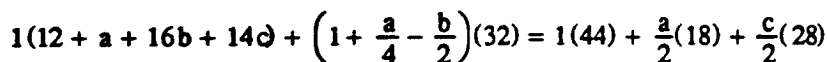
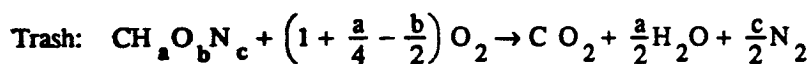
Code	Compound	Formula	Molecular Weight	Energy Value (kcal/g)
C	Carbohydrate	C ₆ H ₁₂ O ₆	180	4
P	Protein	C ₄ H ₅ ON	83	4
F	Fat	C ₁₆ H ₃₂ O ₂	256	9
B	Fiber	C ₆ H ₁₀ O ₅	162	0
L	Lignin	C ₁₀ H ₁₁ O ₂	163	0

Table 3. Chemical reactions occurring in the CELSS system.

Crew Cabin



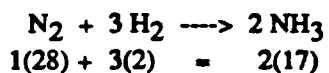
Waste Combustor



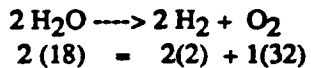
Nonedible Plant: $\text{CH}_{\text{npx}}\text{O}_{\text{npy}}\text{N}_{\text{npz}} + (1+0.25\text{npx}-0.5\text{npy})\text{O}_2 \rightarrow \text{CO}_2 + 0.5\text{npx H}_2\text{O} + 0.5\text{npz N}_2$

$$1(12+\text{npx}+16\text{npy}+14\text{npz}) + (1+0.25\text{npx}-0.5\text{npy})32 = 1(44) + 0.5\text{npx}(18) + 0.5\text{npz}(28)$$

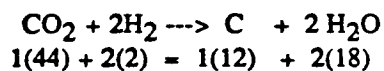
Ammonia Synthesizer



Water Electrolyzer



Bosch Reactor



Plant Growth

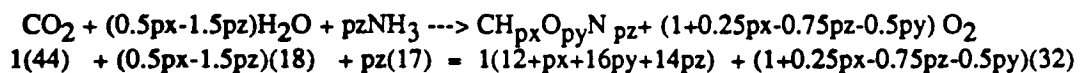


Table 4. Control Strategies for Chemical Reactors

Crew Cabin

The metabolic rate of the crew members determines the rate of oxygen and food delivered to the cabin. The metabolic rate represents the "load" on the life support system.

Plant/Algae Reactor

The CO₂ and H₂O flow to the plant/algae reactor will be determined by food consumption rate. The light intensity will be adjusted for the most efficient production of biomass at the required output.

Ammonia Synthesizer

Only the amount of ammonia needed to culture the algae will be produced.

Waste Combustor

The O₂ supply to the waste combustor will be regulated to completely burn all trash, feces, and urine solids fed to the reactor.

Water Electrolyzer

The rate of the electrolyzer may be governed by the oxygen demand or the hydrogen demand, whichever is greater. Generally, the oxygen demand is controlling.

Bosch Reactor

The Bosch reactor will be regulated by the level in the water tank. The rate is adjusted so there is no depletion in the water tank. The Bosch reactor would be shut off if water were accumulating in the tank.

Table 5. Method for calculating composition of food store items.

Item	Composition of Food Item					
	Fraction of Food Store Items (mass fraction)	Carbohydrate (mass fraction)	Protein (mass fraction)	Fat (mass fraction)	Fiber (mass fraction)	Water (kg water/kg dry food)
1	x_1	FSC_1	FSP_1	FSF_1	FSB_1	FSW_1
2	x_2	FSC_2	FSP_2	FSF_2	FSB_2	FSW_2
3	x_3	FSC_3	FSP_3	FSF_3	FSB_3	FSW_3
.
.
n	x_n	FSC_n	FSP_n	FSF_n	FSB_n	FSW_n
	$\overline{\Sigma x_n}$	$\overline{\Sigma x_n FSC_n}$	$\overline{\Sigma x_n FSP_n}$	$\overline{\Sigma x_n FSF_n}$	$\overline{\Sigma x_n FSB_n}$	$\overline{\Sigma x_n FSW_n}$

$$1 = FSC_n + FSP_n + FSF_n + FSB_n \text{ (condition)}$$

$$1 = \Sigma x_n \text{ (condition)}$$

$$FSC_t = \Sigma x_n FSC_n$$

$$FSP_t = \Sigma x_n FSP_n$$

$$FSF_t = \Sigma x_n FSF_n$$

$$FSB_t = \Sigma x_n FSB_n$$

$$FSW_t = \Sigma x_n FSW_n$$

Table 6. Composition of some food items.³⁰

Item	Composition (dry, ash-free basis)				
	Carbohydrate (mass fraction)	Protein (mass fraction)	Fat (mass fraction)	Fiber (mass fraction)	FSW (g H ₂ O/g dry food)
Pot Roast Beef	0	0.521	0.479	0	1.01
American Cheese	0.034	0.422	0.544	0	0.73
Roasted Chicken (white meat)	0	0.903	0.097	0	1.82
Poached Egg	0.032	0.506	0.462	0	2.92
Baked Flounder	0	0.785	0.215	0	1.52
Shrimp (raw)	0.074	0.887	0.039	0	3.83
Red Bean (dried)	0.672	0.262	0.017	0.049	0.12
Cashew Nut	0.303	0.187	0.495	0.015	0.05
Corn	0.801	0.134	0.038	0.027	2.80
White Rice (cooked)	0.916	0.076	0.004	0.004	2.76

Table 7. Method for calculating composition of edible plants.

Item	Fraction of Plant Production (mass fraction)	Composition of Food Item				
		Carbohydrate (mass fraction)	Protein (mass fraction)	Fat (mass fraction)	Fiber (mass fraction)	Water (kg water/ kg dry plant)
1	j_1	EPC_1	EPP_1	EPF_1	EPB_1	EPW_1
2	j_2	EPC_2	EPP_2	EPF_2	EPB_2	EPW_2
3	j_3	EPC_3	EPP_3	EPF_3	EPB_3	EPW_3
.
.
n	j_n	EPC_n	EPP_n	EPF_n	EPB_n	EPW_n
	$\overline{\Sigma j_n}$	$\overline{\Sigma j_n EPC_n}$	$\overline{\Sigma j_n EPP_n}$	$\overline{\Sigma j_n EPF_n}$	$\overline{\Sigma j_n EPB_n}$	$\overline{\Sigma j_n EPW_n}$

$$1 = EPC_n + EPP_n + EPF_n + EPB_n \text{ (condition)}$$

$$1 = \Sigma j_n \text{ (condition)}$$

$$EPC_t = \Sigma j_n EPC_n$$

$$EPP_t = \Sigma j_n EPP_n$$

$$EPF_t = \Sigma j_n EPF_n$$

$$EPB_t = \Sigma j_n EPB_n$$

$$EPW_t = \Sigma j_n EPW_n$$

$$\begin{aligned} EPC_{Carbon} &= \frac{6(12)}{180} EPC_t + \frac{4(12)}{83} EPP_t + \frac{16(12)}{256} EPF_t + \frac{6(12)}{162} EPB_t \\ &= 0.4EPC_t + 0.578EPP_t + 0.75EPF_t + 0.444EPB_t \end{aligned}$$

$$\begin{aligned} EPH_{Hydrogen} &= \frac{12}{180} EPC_t + \frac{5}{83} EPP_t + \frac{32}{256} EPF_t + \frac{10}{162} EPB_t \\ &= 0.0667EPC_t + 0.0602EPP_t + 0.125EPF_t + 0.0617EPB_t \end{aligned}$$

$$\begin{aligned} EPO_{Oxygen} &= \frac{6(16)}{180} EPC_t + \frac{1(16)}{83} EPP_t + \frac{2(16)}{256} EPF_t + \frac{5(16)}{162} EPB_t \\ &= 0.5333EPC_t + 0.1927EPP_t + 0.125EPF_t + 0.4938EPB_t \end{aligned}$$

$$EPN_{Nitrogen} = \frac{1(14)}{83} EPP_t = 0.1687EPP_t$$

$$epx = \frac{12}{1} \frac{EPH_{Hydrogen}}{EPC_{Carbon}} = 12 \frac{EPH_{Hydrogen}}{EPC_{Carbon}}$$

$$epy = \frac{12}{16} \frac{EPOxygen}{EPCarbon} = 0.75 \frac{EPOxygen}{EPCarbon}$$

$$epz = \frac{12}{14} \frac{EPNitrogen}{EPCarbon} = 0.857 \frac{EPNitrogen}{EPCarbon}$$

Table 8. Residue coefficients

Item	Fraction of Plant Production (mass fraction)	Residue Coefficient (kg dry residue/kg dry edible plant)
1	j ₁	RC ₁
2	j ₂	RC ₂
3	j ₃	RC ₃
.	.	.
.	.	.
.	.	.
n	j _n	RC _n
		$\overline{\Sigma j_n RC_n}$

$$PW = \Sigma j_n RC_n$$

$$k_1 = \frac{j_1 RC_1}{PW}$$

$$k_2 = \frac{j_2 RC_2}{PW}$$

$$k_3 = \frac{j_3 RC_3}{PW}$$

.

.

.

$$k_n = \frac{j_n RC_n}{PW}$$

Table 9. Method for calculating composition of nonedible plant residue.

Item	Fraction of Nonedible Plant Pro- duction (mass fraction)	C (mass fraction)	P (mass fraction)	F (mass fraction)	B (mass fraction)	L (mass fraction)	W (g water/ g dry matter)
1	k_1	NPC_1	NPP_1	NPF_1	NPB_1	NPL_1	NPW_1
2	k_2	NPC_2	NPP_2	NPF_2	NPB_2	NPL_2	NPW_2
3	k_3	NPC_3	NPP_3	NPF_3	NPB_3	NPL_3	NPW_3
.
.
.
n	k_n	NPC_n	NPP_n	NPF_n	NPB_n	NPL_n	NPW_n
	Σk_n	$\Sigma k_n NPC_n$	$\Sigma k_n NPP_n$	$\Sigma k_n NPF_n$	$\Sigma k_n NPB_n$	$\Sigma k_n NPL_n$	$\Sigma k_n NPW_n$

$$1 = NPC_n + NPP_n + NPF_n + NPB_n + NPL_n \text{ (condition)}$$

$$1 = \Sigma k_n \text{ (condition)}$$

$$NPC_t = \Sigma k_n NPC_n$$

$$NPP_t = \Sigma k_n NPP_n$$

$$NPF_t = \Sigma k_n NPF_n$$

$$NPB_t = \Sigma k_n NPB_n$$

$$NPL_t = \Sigma k_n NPL_n$$

$$NPW_t = \Sigma k_n NPW_n$$

$$NPC_{Carbon} = 0.4 NPC_t + 0.578 NPP_t + 0.75 NPF_t + 0.444 NPB_t + 0.736 NPL_t$$

$$NPHydrogen = 0.0667 NPC_t + 0.0602 NPP_t + 0.125 NPF_t + 0.0617 NPB_t + 0.0675 NPL_t$$

$$NPOxygen = 0.5333 NPC_t + 0.1927 NPP_t + 0.125 NPF_t + 0.4938 NPB_t + 0.1963 NPL_t$$

$$NPNitrogen = 0.1687 NPP_t$$

$$npx = \frac{12}{1} \frac{NPHydrogen}{NPC_{Carbon}} = 12 \frac{NPHydrogen}{NPC_{Carbon}}$$

$$npy = \frac{12}{16} \frac{NPOxygen}{NPC_{Carbon}} = 0.75 \frac{NPOxygen}{NPC_{Carbon}}$$

$$npz = \frac{12}{14} \frac{NPNitrogen}{NPC_{Carbon}} = 0.857 \frac{NPNitrogen}{NPC_{Carbon}}$$

Table 10. Method for calculating composition of entire plant.

$$PCarbon = \frac{12}{12 + epx + 16epy + 14epz} + \frac{12(PW)}{12 + npx + 16npy + 14npz}$$

$$PHydrogen = \frac{epx}{12 + epx + 16epy + 14epz} + \frac{npx(PW)}{12 + npx + 16npy + 14npz}$$

$$POxygen = \frac{16epy}{12 + epx + 16epy + 14epz} + \frac{16npy(PW)}{12 + npx + 16npy + 14npz}$$

$$PNitrogen = \frac{14epz}{12 + epx + 16epy + 14epz} + \frac{14npz(PW)}{12 + npx + 16npy + 14npz}$$

$$px = \frac{12}{1} \frac{PHydrogen}{PCarbon} = 12 \frac{PHydrogen}{PCarbon}$$

$$py = \frac{12}{16} \frac{POxygen}{PCarbon} = 0.75 \frac{POxygen}{PCarbon}$$

$$pz = \frac{12}{14} \frac{PNitrogen}{PCarbon} = 0.857 \frac{PNitrogen}{PCarbon}$$

Table 11. Method for calculating composition of food eaten.

$$C_t = x_{food\ stores} FSC_t + (1 - x_{food\ stores}) EPC_t$$

$$P_t = x_{food\ stores} FSP_t + (1 - x_{food\ stores}) EPP_t$$

$$F_t = x_{food\ stores} FSF_t + (1 - x_{food\ stores}) EPF_t$$

$$B_t = x_{food\ stores} FSB_t + (1 - x_{food\ stores}) EPB_t$$

$$w_{food} = x_{food\ stores} FSW_t + (1 - x_{food\ stores}) EPW$$

Table 12. Calculation of the elemental composition of trash.

Item	Fraction of Total Trash (mass fraction)	Composition of Trash Item			
		C (mass fraction)	H (mass fraction)	O (mass fraction)	N (mass fraction)
1	y_1	TC_1	TH_1	TO_1	TN_1
2	y_2	TC_2	TH_2	TO_2	TN_2
3	y_3	TC_3	TH_3	TO_3	TN_3
.
.
n	y_n	TC_n	TH_n	TO_n	TN_n
	$\overline{\Sigma y_n}$	$\overline{\Sigma y_n TC_n}$	$\overline{\Sigma y_n TH_n}$	$\overline{\Sigma y_n TO_n}$	$\overline{\Sigma y_n TN_n}$

$$1 = TC_n + TH_n + TO_n + TN_n \text{ (condition)}$$

$$1 = \Sigma y_n \text{ (condition)}$$

$$TC_t = \Sigma y_n TC_n$$

$$TH_t = \Sigma y_n TH_n$$

$$TO_t = \Sigma y_n TO_n$$

$$TN_t = \Sigma y_n TN_n$$

Trash Formula = $C H_a O_b N_c$

$$a = \frac{12}{1} \frac{TH_t}{TC_t} = 12 \frac{TH_t}{TC_t}$$

$$b = \frac{12}{16} \frac{TO_t}{TC_t} = 0.75 \frac{TO_t}{TC_t}$$

$$c = \frac{12}{14} \frac{TN_t}{TC_t} = 0.857 \frac{TN_t}{TC_t}$$

Table 13. Metabolic heat associated with various activities.¹⁹

Activity	Metabolic Heat (W)
Sleep	84
Resting (sitting)	118
Very Light Activity (taking notes)	140
Light Activity (vehicle repair)	237
Moderate Activity (cycling 8 mi/h)	398
Heavy Activity (cycling 23 mi/h)	683
Very Heavy Activity (rowing 3.5 mi/h)	767

Table 14. Composition of *Dry Feces.²²

	Mass Fraction
Bacteria	0.3
Fat	0.1-0.2
Inorganic Matter	0.1-0.2
Protein	0.02-0.03
Fiber	0.3

*Note: wet feces contain about 75% water.

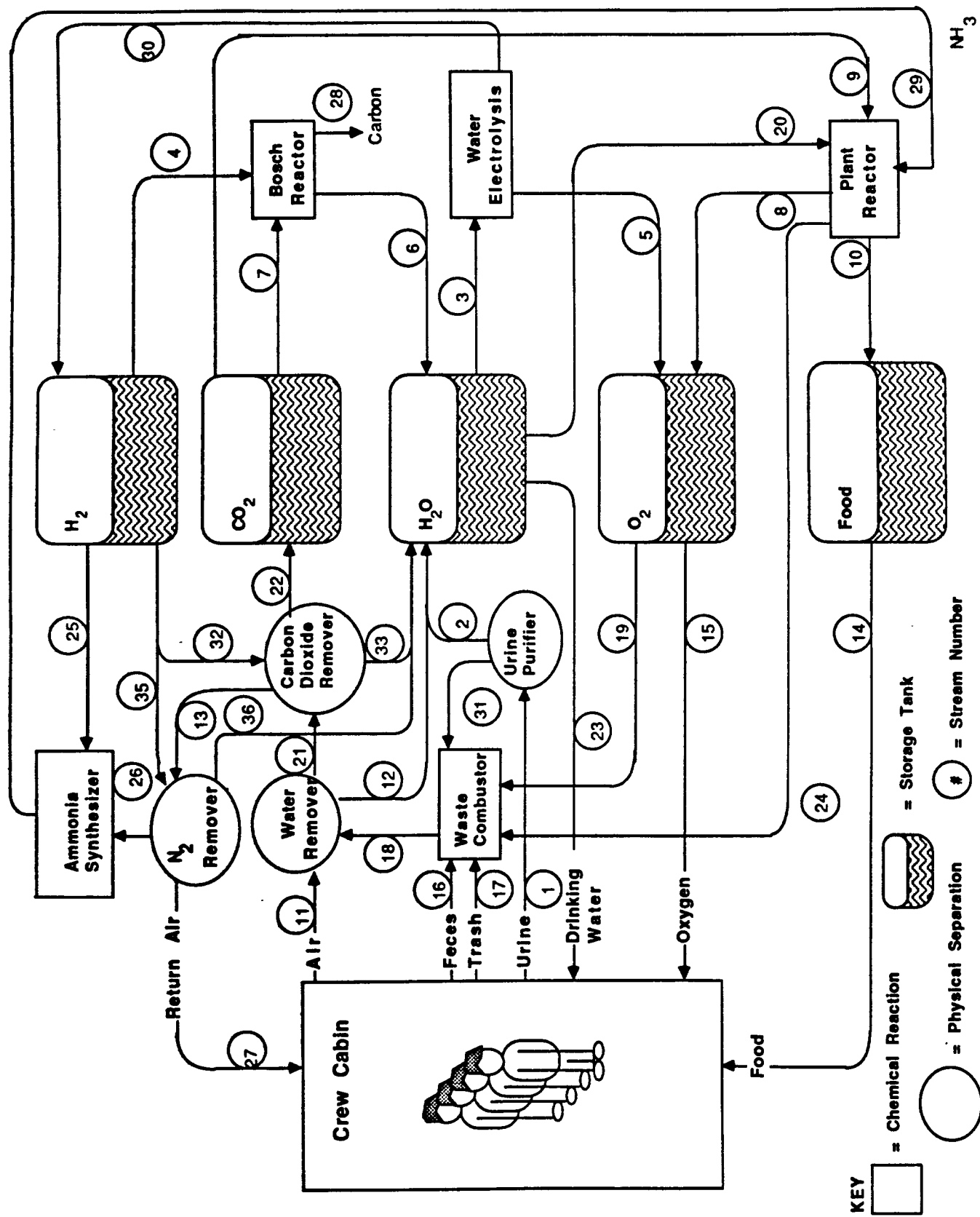


Figure 1. CELSS schematic using higher plants or algae for food and oxygen production.

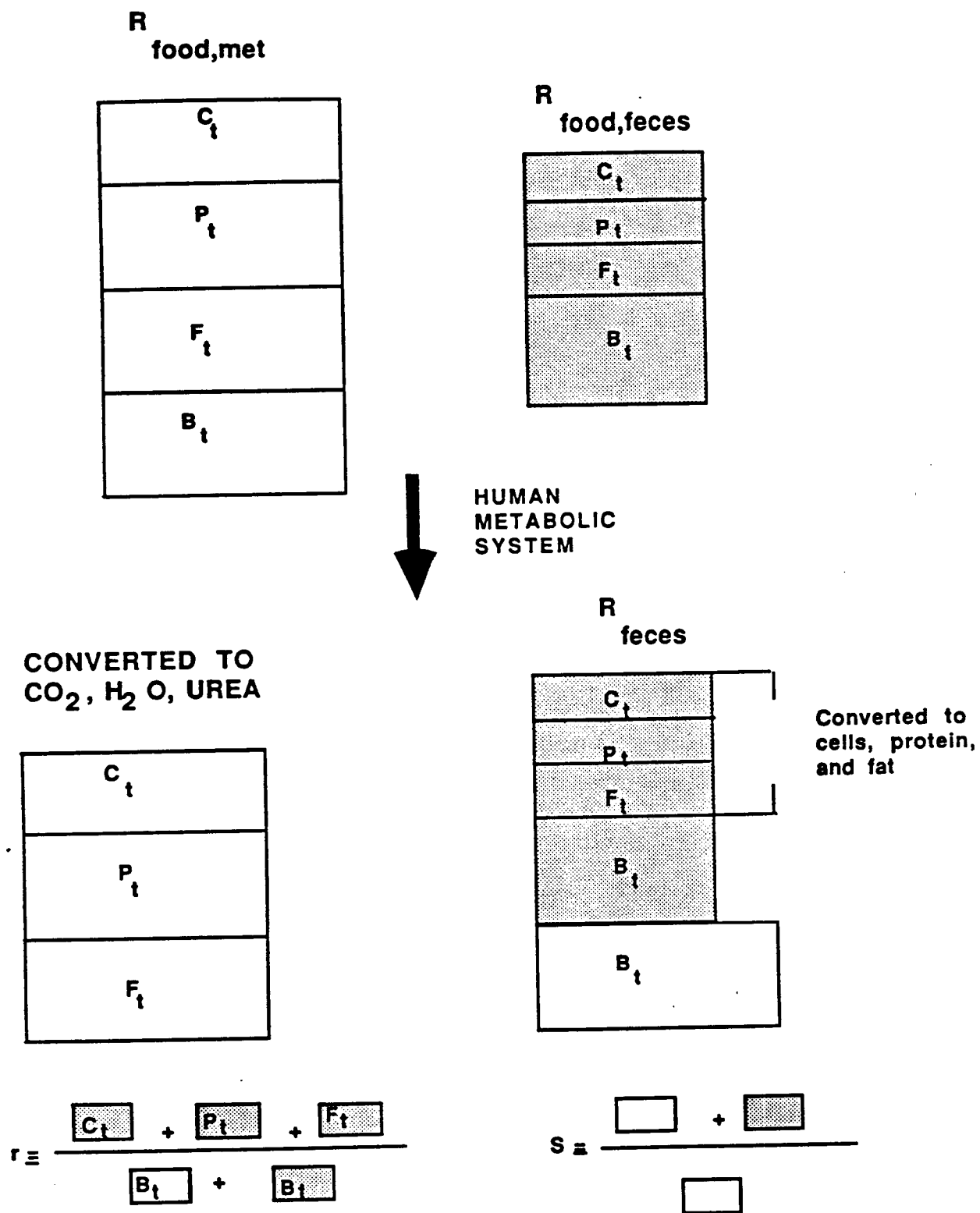


Figure 2. Schematic representation of the ultimate disposition of the food consumed.

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Appendix C

**BOSCH AND SABATIER SUBSYSTEM
COMPARISON FOR THE CO₂ REDUCTION
PROCESS**

Prepared by

**M.E. Moses
Mechanical Engineering**

BOSCH AND SABATIER SUBSYSTEM COMPARISON FOR THE CO₂ REDUCTION PROCESS

The Bosch and Sabatier processes are leading technology options for reducing carbon dioxide and are primary subsystem candidates for regenerative purposes in manned spacecraft (ie., Space Station). Each reduces CO₂ by catalytic reaction with hydrogen (H₂), however the end products differ because of process catalyst and temperature. The Bosch process produces carbon and water while the Sabatier produces methane and water.

Oxygen (O₂) can be returned for human metabolic consumption through electrolysis of water. Hydrogen resulting from electrolysis can be used to feed the reduction process. Carbon is lost from the system as solid carbon (Bosch) or methane (Sabatier).

To aid modeling studies being conducted by RECON team members, the following data for the Bosch and Sabatier reactors has been accumulated from several recent references cited in the bibliography.

Each system has been sized, fabricated and successfully operated by Life Systems, Inc., Cleveland, OH, to accommodate CO₂ for a three-person crew.

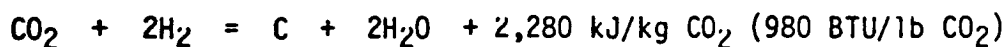
The following assumptions apply to data provided for each system:

- * Crew Size: 3
- * CO₂ Reduction Requirement: 1.0 kg/person (2.2 lb/person) per day
- * Equivalent weight Penalties:
 - Power, kg/w (lb/w) AC: 0.32 (0.71)
DC: 0.27 (0.59)
 - Heat Rejection, kg/w (lb/w)
 - To liquid: 0.083 (0.184)
 - To air: 0.198 (0.437)

The system descriptions and pertinent data are as follows:

BOSCH PROCESS/DESCRIPTION:

The Bosch process is:



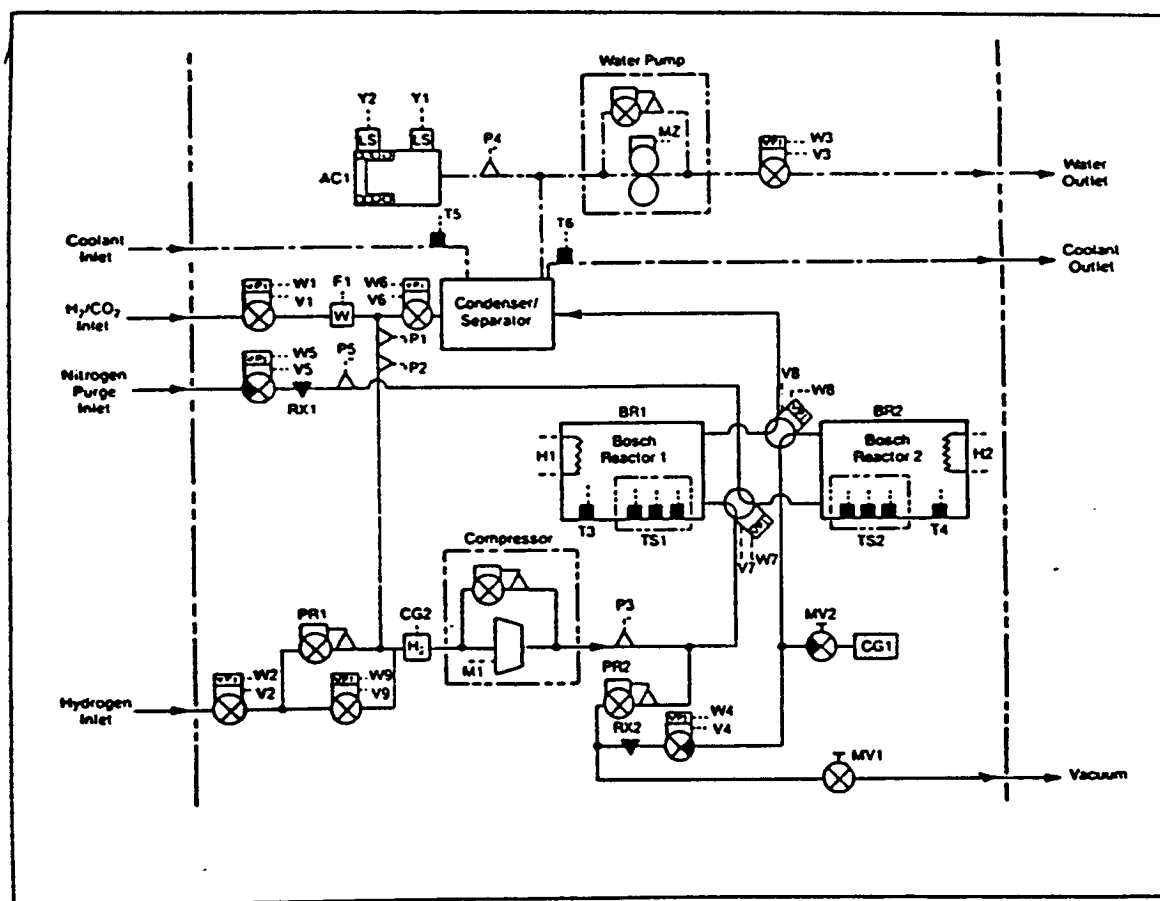
Reaction temperature: 800-1,000 K (980-1,340F)

Catalyst: Iron, cobalt or nickel

Single pass efficiency: <10%; complete conversion obtained by gas recycling

Nominal CO₂ Reduction Rate: kg/h(lb/h) = 0.125(0.275)

Bosch Subsystem Mechanical Schematic



Subsystem weight:

69.1 kg (152.7 lbs)

Power Requirement:(W)

AC, 210 , DC, 19: Total 229 W

Heat Rejection:

W to air: 52

W to Liquid: 260

Total 312 W

Volume: (estimate by T. Rogers)

3.0 ft³

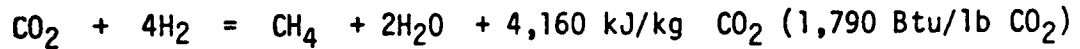
Water production rate: 0.102 kg/h (0.225 lb/h)

Carbon production rate: 0.034 kg/h (0.075 lb/h)

Based on a 90-day mission, expendables for the Bosch process would include canister, blanket, filter, catalyst and carbon formed at a weight of 228.6 lb.

SABATIER PROCESS/DESCRIPTION:

The Sabatier process is:

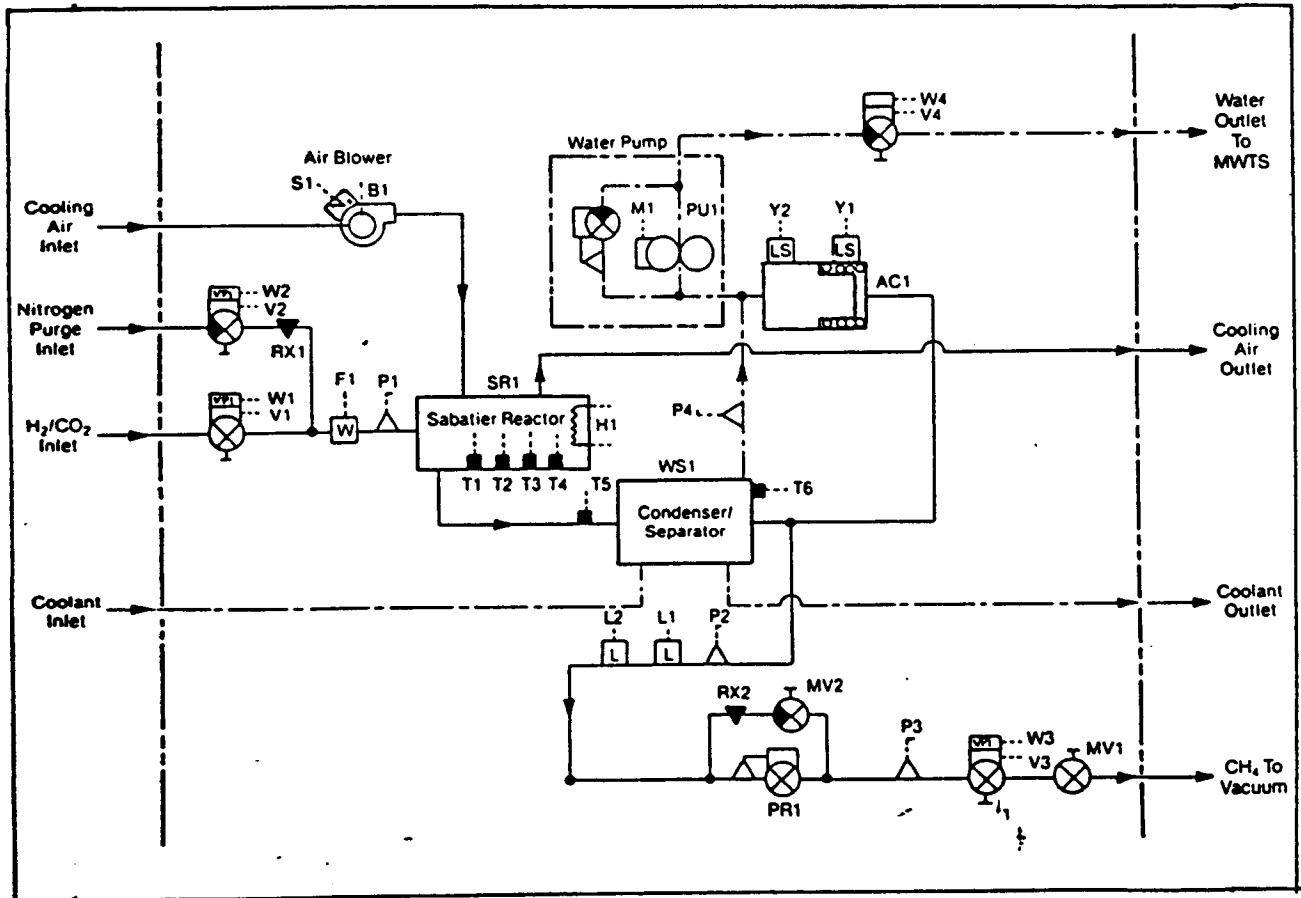


Reaction temperature: 450-800 K (350-980F)

Catalyst: Ruthenium

Single pass efficiency: >98%

Sabatier Subsystem Mechanical Schematic



Subsystem weight:

21.3 kg (47.2 lbs)

Power requirements: (W)

AC, 40 : DC, 17: Total 57 W

Heat Rejection:

W to air: 129

W to Liquid: 72 Total 201 W

Volume:

0.8 ft³

Water production rate: 0.103 kg/h (0.228 lb/h)

Methane production rate: 0.045 kg/h (0.098 lb/h)

Based on a 90-day mission, expendable weight for the Sabatier process would include 211.7 lb methane (no provision made for storage container weight). Based on the information available at this time, methane is off-gassed from the system via venting and there is no indication that studies are in progress to recycle the methane via cracking or to store this byproduct.

Side Reactions:

Bosch Process: Carbon monoxide (CO) is an intermediate product in the process, however due to recycling necessitated by the low first pass efficiency of the Bosch process, CO is converted in the second step to H₂O and carbon (C). (K. Otsuji, et.al., 1987).

Sabatier Process: Methane (CH₄) is a principal product of this process and could leak from the system.

REFERENCES

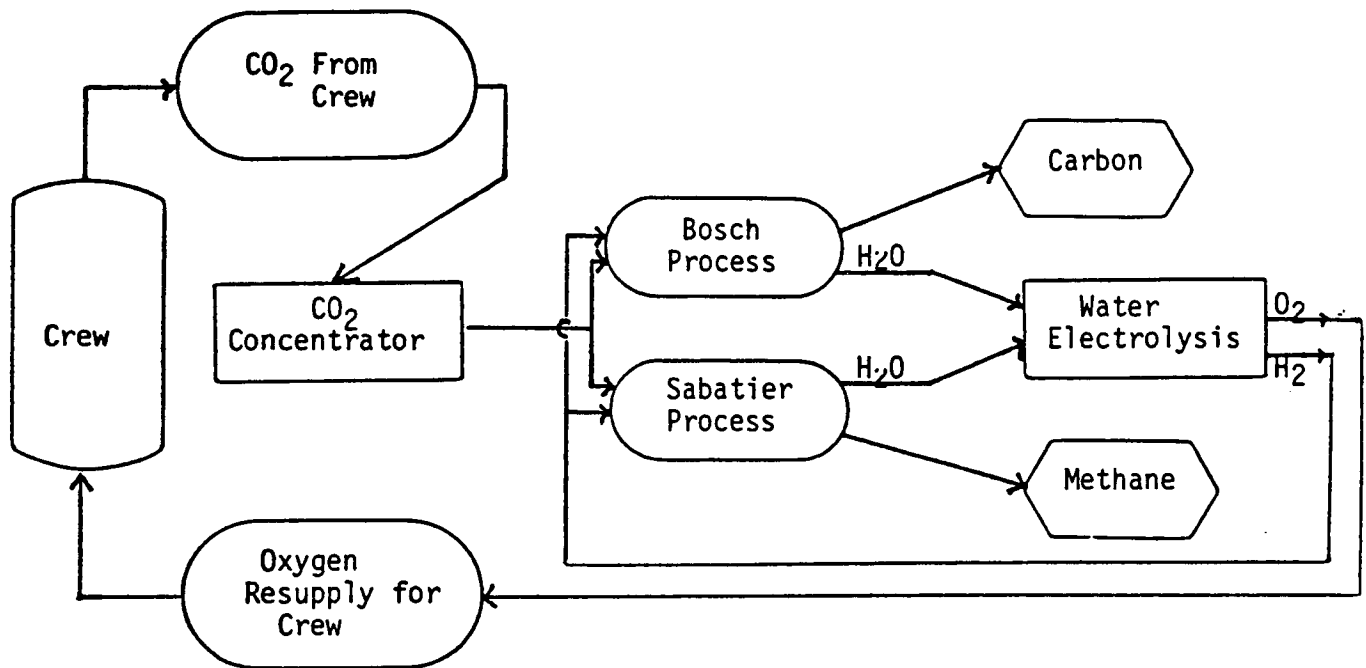
1. Otsuji, K., O. Hanabusa, T. Sawada, S. Satoh and M. Minemoto. "An Experimental Study of the Bosch and the Sabatier CO₂ Reduction Processes" Paper No. 871517, Intersociety Conference on Environmental Systems, Seattle, WA: July, 1987.

2. L. Spina and M. C. Lee. "Comparison of CO₂ Reduction Process - Bosch and Sabatier." Paper No. 851343, Intersociety Conference on Environmental Systems, San Francisco, CA: July, 1985.

BOSCH AND SABATIER SUBSYSTEM INTERFACES

The preceeding information on the Bosch and Sabatier defined their respective process characteristics for CO₂ reduction. In the Ecological Control Life Support System (ECLSS) scheme of integrated subsystems, the Bosch and Sabatier require interface systems on both the input and output sides. Although not identical, there are 2 major aspects in which the same subsystem (CO₂ concentrator) can be interfaced with the Bosch and Sabatier on the input side, while a water electrolysis subsystem is the common output side interface.

A simple graphic explanation of this relationship is shown as follows:



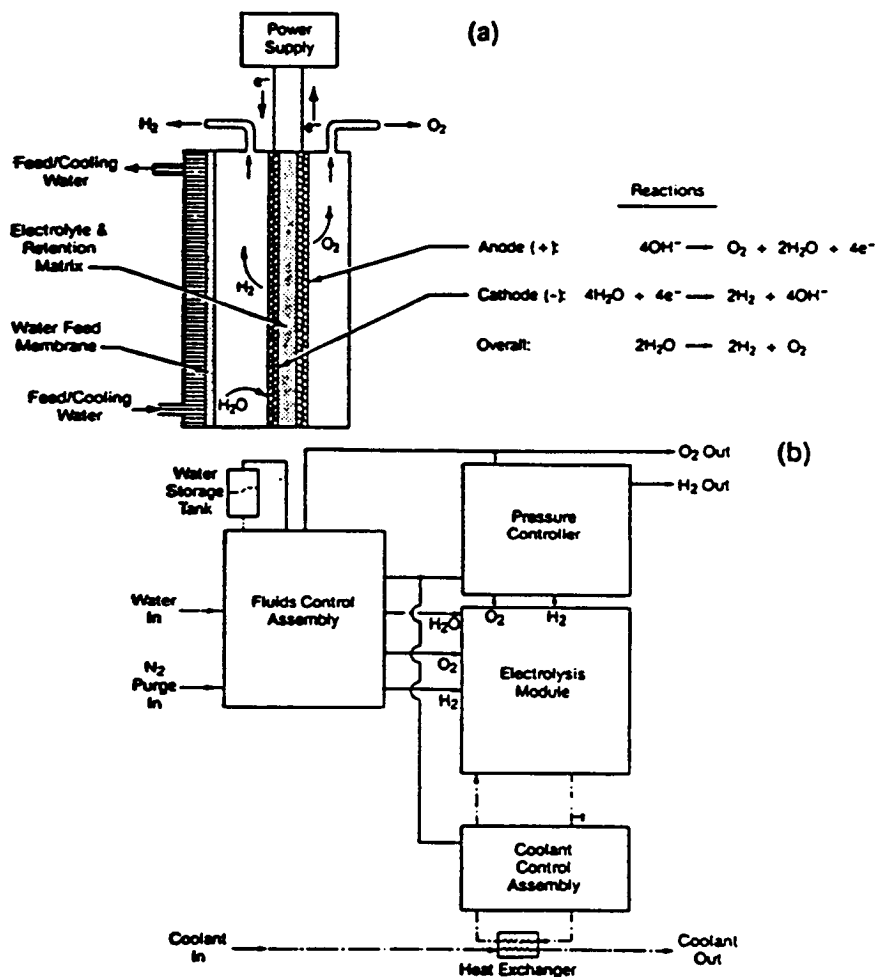
STATIC FEED WATER ELECTROLYSIS SUBSYSTEM:

Electrolysis of water has direct application to support several diversified spaceflight functions; ECLSS, Propulsion and Reboost Systems, Extravehicular Activity(EVA), and Electric Power Systems(EPS). Oxygen generated from water electrolysis can be used for crew metabolic consumption, EVA backpacks, air locks, and leakage makeup. Hydrogen from the process becomes a reactant for CO₂ removal from metabolic air, CO₂ reduction(Bosch or Sabatier process), propulsion and reboost systems and for fuel cell electric power generation.

A Static Feed Electrolyzer(SFE) has been developed by Life Systems, Inc., Cleveland, OH (Fortunato and Burke, 1987), and is being integrated into the Module Simulator at Marshall Space Flight Center(MSFC) for conducting an integrated test in 1987(Jackson, et.al., 1987).

STATIC FEED ELECTROLYZER DESCRIPTION:

The water electrolysis process reactor(a) and functional block diagram (b) are shown below(From Fortunato and Burke, 1987).



The Static Feed Electrolyzer operating characteristics are as follows:

Crew Size	3
Number of Cells	12
Active Area per Cell, $\text{m}^2(\text{ft}^2)$	0.023(0.25)
Current Density (Nominal), mA/cm^2 (ASF)	129.2 (120)
Cell Voltage (Nominal), V(a)	1.65
Power Consumed, W	577
Waste Heat Produced, W	59.6(b)
O_2 Generated, Kg/day (lb/day)	2.50(5.52)
H_2 Generated, Kg/day (lb/day)	0.32(0.70)
Water Consumed, Kg/day (lb/day)(c)	2.82 (6.22)

(a) At normal mode temperature of 150°F

(b) $(1.65\text{V} - 1.48\text{V}) \times (12 \text{ cells}) \times (29.2\text{A}) = 59.6\text{W}$

(c) 0.02 Kg/day (0.04 lb/day) as O_2 Humidification
0.04 Kg/day (0.09 lb/day) as H_2 Humidification

Weight
Volume

80 lb
1.6 ft^3

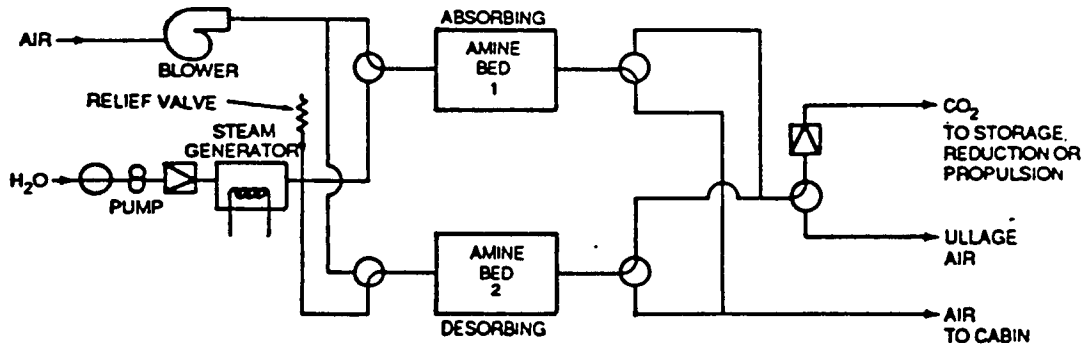
CO₂ REMOVAL AND CONCENTRATION:

NASA is currently evaluating various hardware prototypes for Air Revitalization Subsystems(ARS) for application to Space Station ECLSS simulation studies. Three different concepts are currently being considered for CO₂ removal from the cabin atmosphere. They are as follows:

- * 4-Bed Molecular Sieve(4BMS) which is based on adsorption by a molecular sieve sorbent
- * Electrochemical Depolarized CO₂ Concentrator(EDC) which uses electrochemical separation
- * Solid Amine Water Desorbed CO₂ Concentrator(SAWD) which is based on absorption by solid amine sorbent

To expedite making appropriate information available for modelling purposes, the solid amine water desorbed CO₂ concentration method will be used at this time. The data is 2-3 years old (reported in 1985), but should be satisfactory until they can be updated with newer information which I believe to be available, but have not gained access to as of this date.

The subsystem block diagram for the Solid Amine Water Desorbed CO₂ Concentration process is:



From C.D. Ray, et.al., 1987

In 1983, Hamilton Standard began developing the SAWD II preprototype which was a modification of a successfully operated previous model (SAWD I). The specifications for the above system are shown on the following page.

SAWD II Specifications

Parameter	Specification
Crew size	3
CO ₂ removal/delivery rate	0.125 kg/hr (0.275 lb/hr)
Cabin PCO ₂	3.0 mmHg
Cabin temperature	292 to 300 K (65 to 80 F)
Cabin relative humidity	35 to 70%
Cabin dew point *	277 to 289 K (39 to 61 F)
Cabin pressure	101 kPa (14.7 psia)
CO ₂ delivery pressure	126.kPa (18.3 psia)
CO ₂ removal package size	0.61 mW x 0.61 mH x 0.79 mD (24" W x 24" H x 31"D)
*Within the relative humidity limits	

The operational and physical characteristic data for the SAWD II is:

	Preprototype	Projected + Flight Design
Number of canisters.....	Two (2)	
Amine weight per canister..	3.9 kg (8.5 lb) (Dry)	
Air flow rate.....	425 lpm (15 cfm)	
Absorption pressure level	101 kPa (14.7 psia)	
Absorption cycle duration*		
50% Relative humidity.....	70 minutes	
35% Relative humidity.....	45 minutes	
70% Relative humidity.....	88 minutes	
System pressure loss..	163mmH ₂ O (6.4 in.)	
CO ₂ desorption pressure level	206 kPa (30 psia)	
System power requirements**	495 watts	460 watts
System weight.....	76.4 Kg (168 lb)	52.3Kg (115lb)
System volume.....	0.30m ³ (10.7ft ³)	.23m ³ (8.2ft ³)

*Desorption cycle durations are the same
 **For hominal conditions at 50% relative humidity
 + If left blank, then same as preprototype

From A.K. Colling, Jr., 1985

REFERENCES

1. Colling, A. K., Jr., T. A. Nalette, R. J. Cusick and R. P. Keysa. "Development Status of Regenerable Solid Amine CO₂ Control Systems." Paper No. 851340, SAE Intersociety Conference on Environmental Systems, San Francisco, CA, July, 1985.
2. Fortunato, F. A. and K. A. Burke. "Static Feed Electrolyzer Technology Advancement for Space Station." Paper No. 871450, SAE Intersociety Conference on Environmental Systems, Seattle WA, July, 1987.
3. Jackson, J. K., E. A. Worden, R. B. Boyda and R. L. Johnson. "Initial Results of Integrated Testing of a Regenerative ECLSS at MSFC." Paper No. 871454, SAE Intersociety Conference on Environmental Systems, Seattle, WA, July, 1987.
4. Ray, C. D., K. Y. Ogle, R. W. Tipps, R. L. Carrasquillo, and P. Wieland. "The Space Station Air Revitalization Subsystem Design Concept." Paper No. 871448, SAE Intersociety Conference on Environmental Systems, Seattle, WA, July, 1987.

EVAPORATOR:

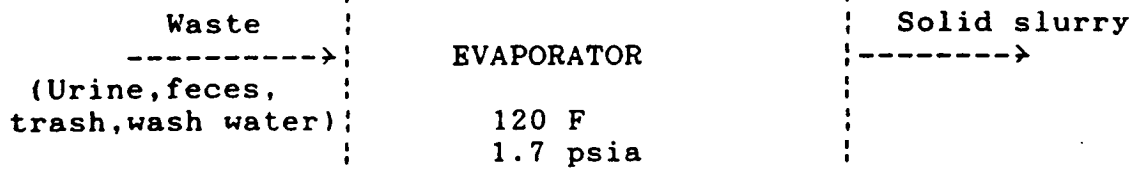
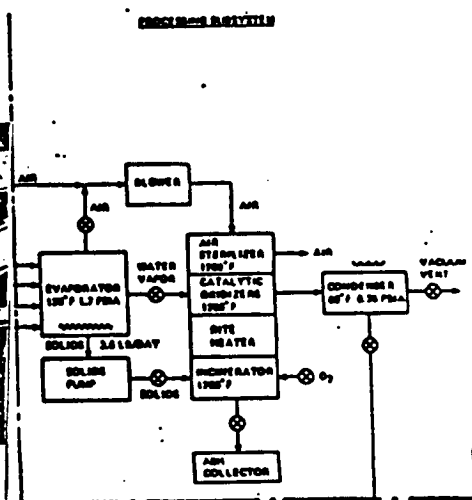
All solids and liquid wastes are collected in the evaporator. The evaporator is a multifunction device in that it evaporates the water, centrifugally separates the solids and the final design will centrifugally separate any liquid carryover from the steam.



Figure 4-11. Evaporator



Figure 4-12. Evaporator (Top Removed)



INPUT:

Feces	:	1.2	lbs/day
Urine	:	14.0	,,
Tap water	:	20.0	,,
Wash water	:	24.0	,,
Trash	:	1.2	,,

Power input	:	800 watts (approx.)
Weight	:	75 lbs

OUTPUT:

Solid slurry

INCINERATOR :

The incinerator processes the solid wastes from the evaporator by vacuum drying, thermal decomposition at 1200 F and incineration. The drying and thermal decomposition steps remove approximately 90-95% of the trash weight; consequently, the incinerator step requires a minimum of oxygen to reduce the solids weight and volume to approximately 99% of the original. All gases are removed from the system via a vacuum vent.

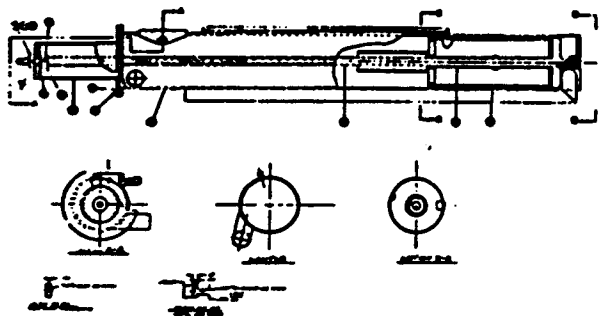
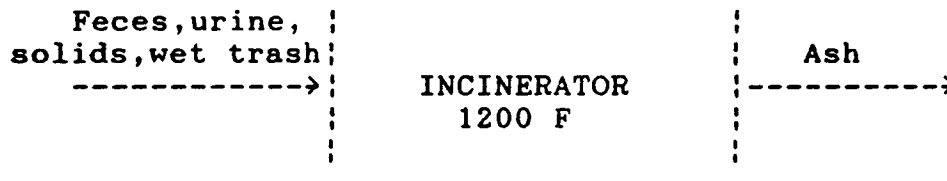
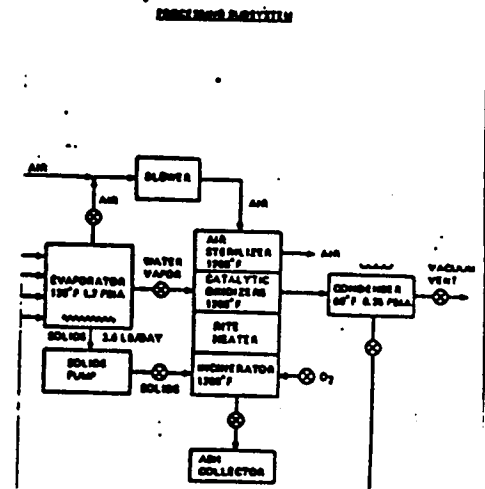


Figure 9-22. Incinerator Assembly



INPUT:

Six days of test--
2939 grams waste

Power input: 72 watts
Weight : 19.7 lbs

OUTPUT:

Ash - 17 grams
(wt. reduction of over 99%)

CONDENSER:

The condenser removes the sensible and latent heat from the steam which exits from the pyrolysis units. Cooling is provided by a liquid coolant pumped through tubes attached to the condenser walls. Only one condenser will be used in the final design. It will be configured to retain the liquid in zero gravity and will permit water removal via a pump. The condenser will also have a port for venting non-condensable gases to vacuum.

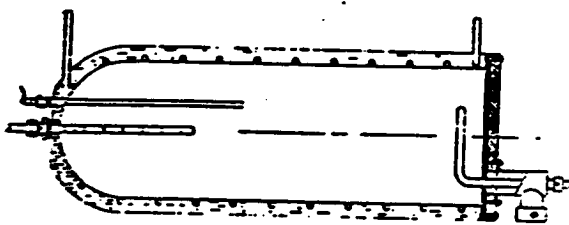
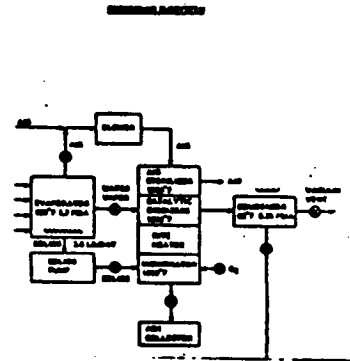


Figure 4-14. Condenser



Water vapor

CONDENSER
60 F
0.25 psia

Liquid water

INPUT:

Water vapor

OUTPUT:

Liquid water

Power input: none
Weight : 11.5 lbs

CATALYTIC OXIDIZERS:

The catalytic oxidizer units process the low pressure steam from the evaporator by heating to 1200 F in the presence of a catalyst and a small amount of oxygen. The impurities in the steam are catalytically oxidized and vented to vacuum when the steam is condensed.

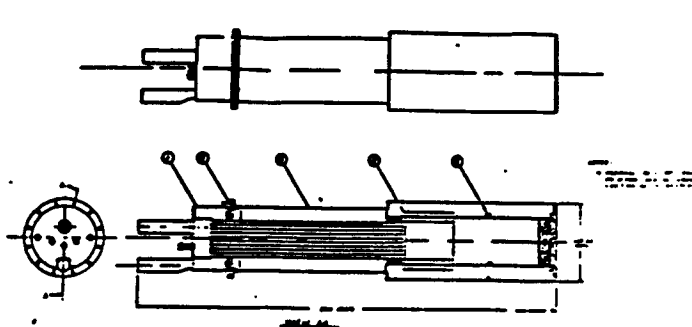
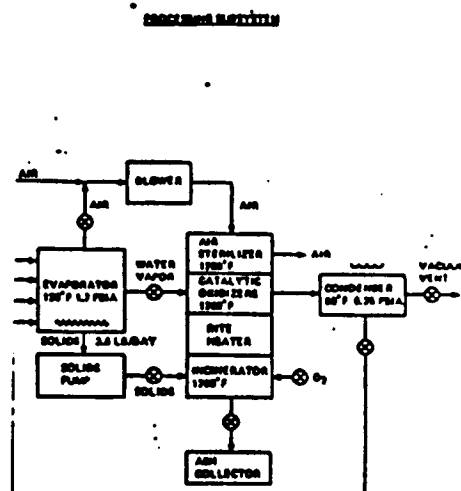


Figure 6-24. Pyrolysis-Catalytic Oxidizer



Impure water vapor

CATALYTIC
OXIDIZERS
1200 F

Pure water vapor

INPUT:

Impure water vapor

OUTPUT:

Avg. water recovery rate 56.0 lb/day
Pick ,, ,, ,, 75.5 ,,
Avg. ,, ,, efficiency 98%

Power input : none
weight : 42.6 lbs

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